QCD FOR THE LHC

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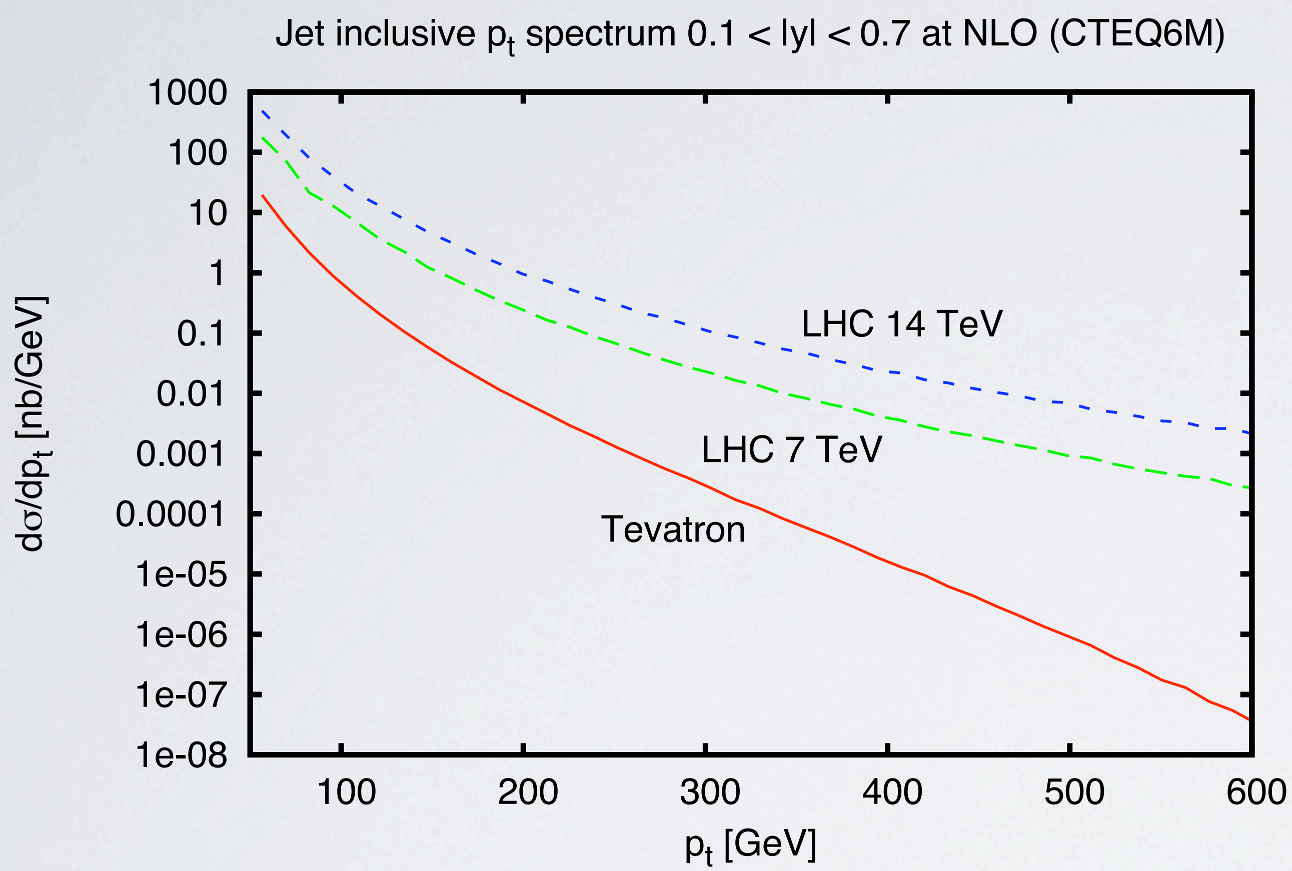
ETH ZURICH

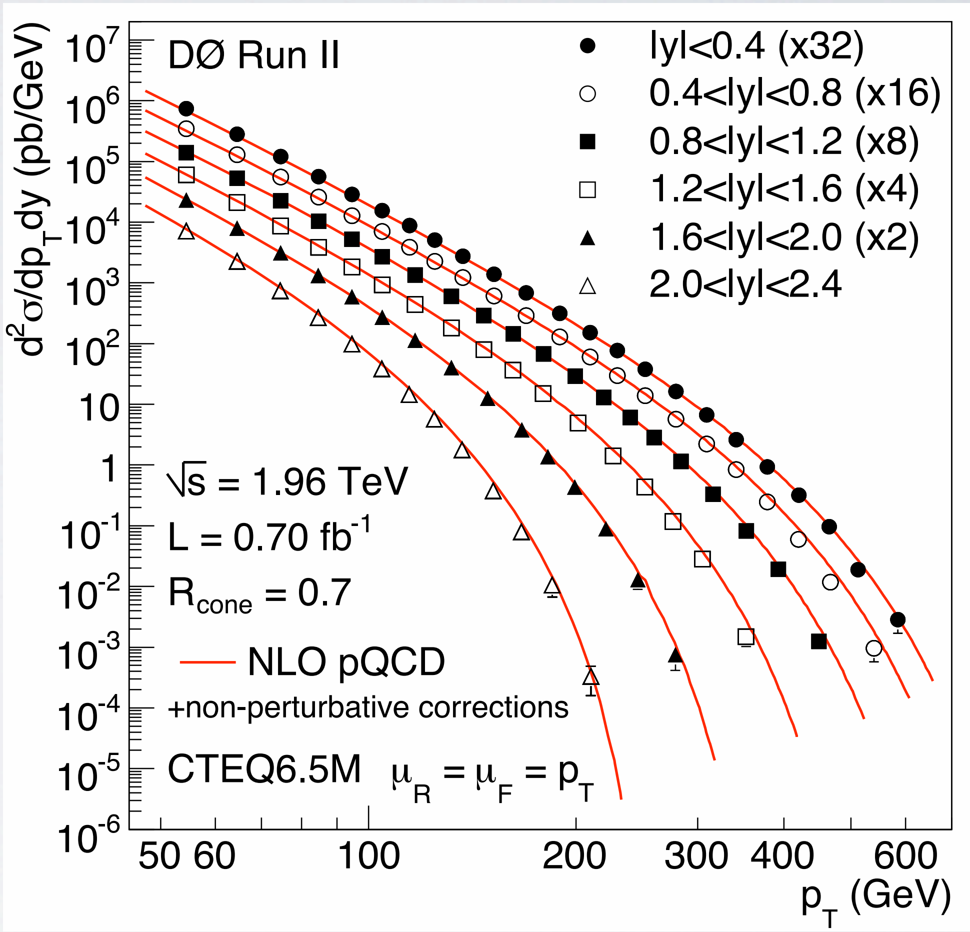
Brookhaven Forum 2010

OUTLINE

- The TEVATRON experience
- QCD for the sake of QCD
- QCD background
- QCD of new physics
- Theoretical breakthroughs and revelations

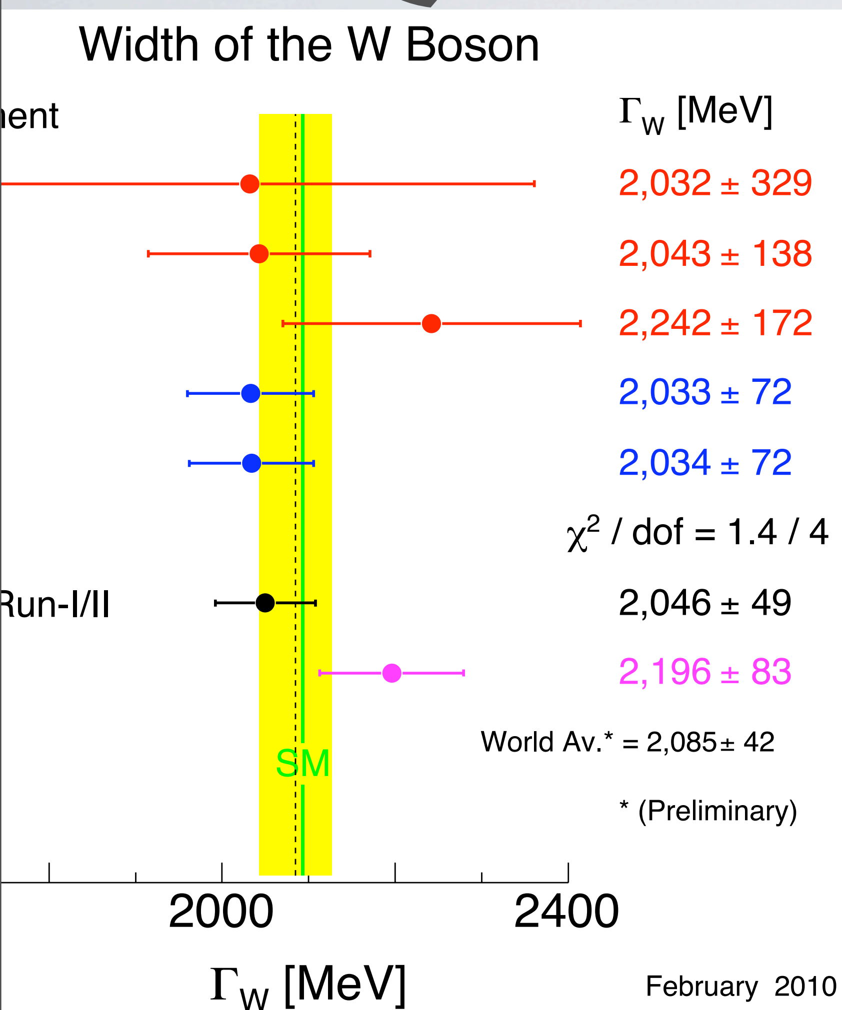
ENERGY WORLD RECORDS

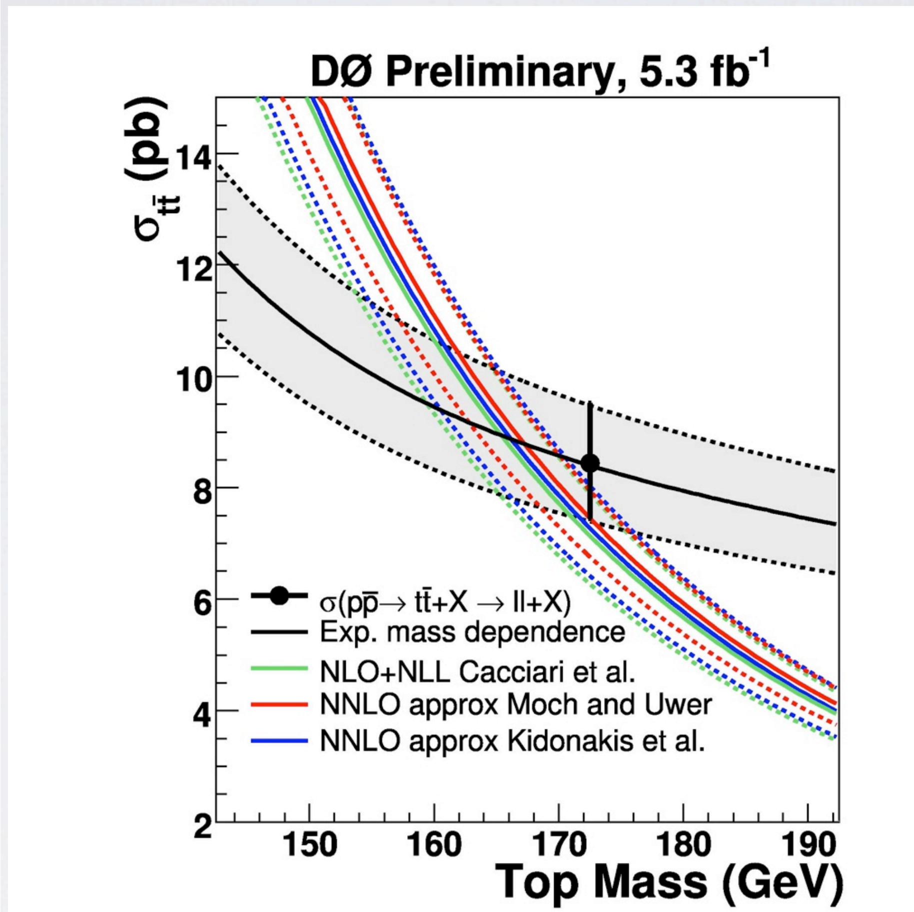


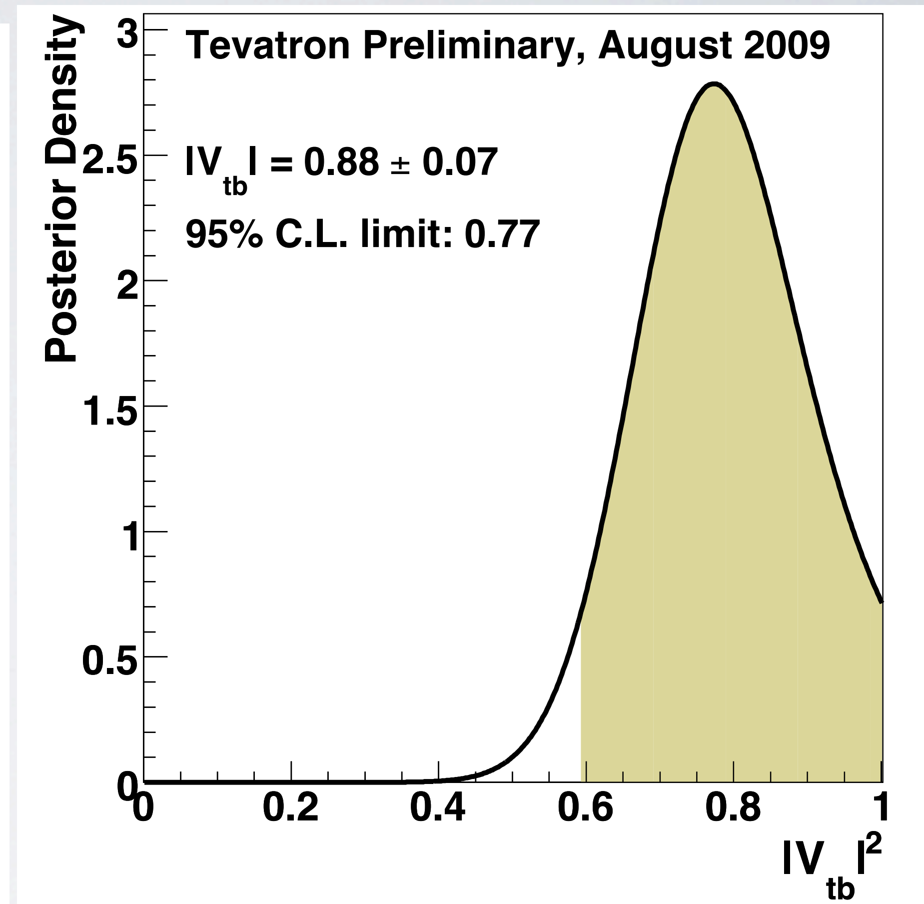


- Tevatron: plethora of data for QCD processes at very high energies.
- Detailed QCD analyses have been published.
- LHC: The next energy frontier, where a proof that QCD is a "domesticated" theory must be furnished.

WHAT ARE THE FACES OF QCD AT THE TEVATRON?

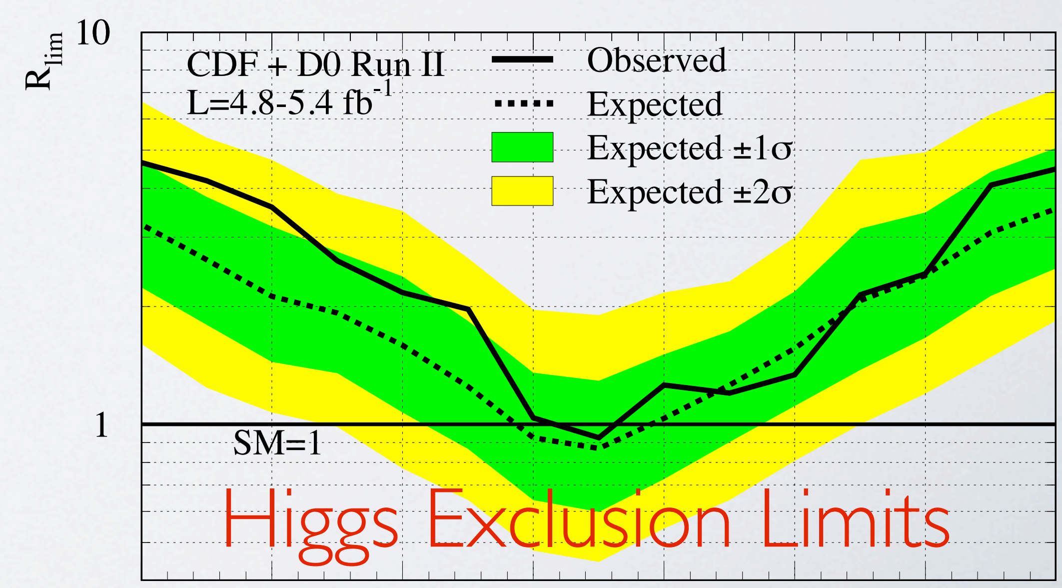






- Precise QCD predictions are essential for almost every analysis.

- Progress in the understanding of high energy physics relies on QCD theory



QCD FOR THE LHC: "RETURN ON INVESTMENT"

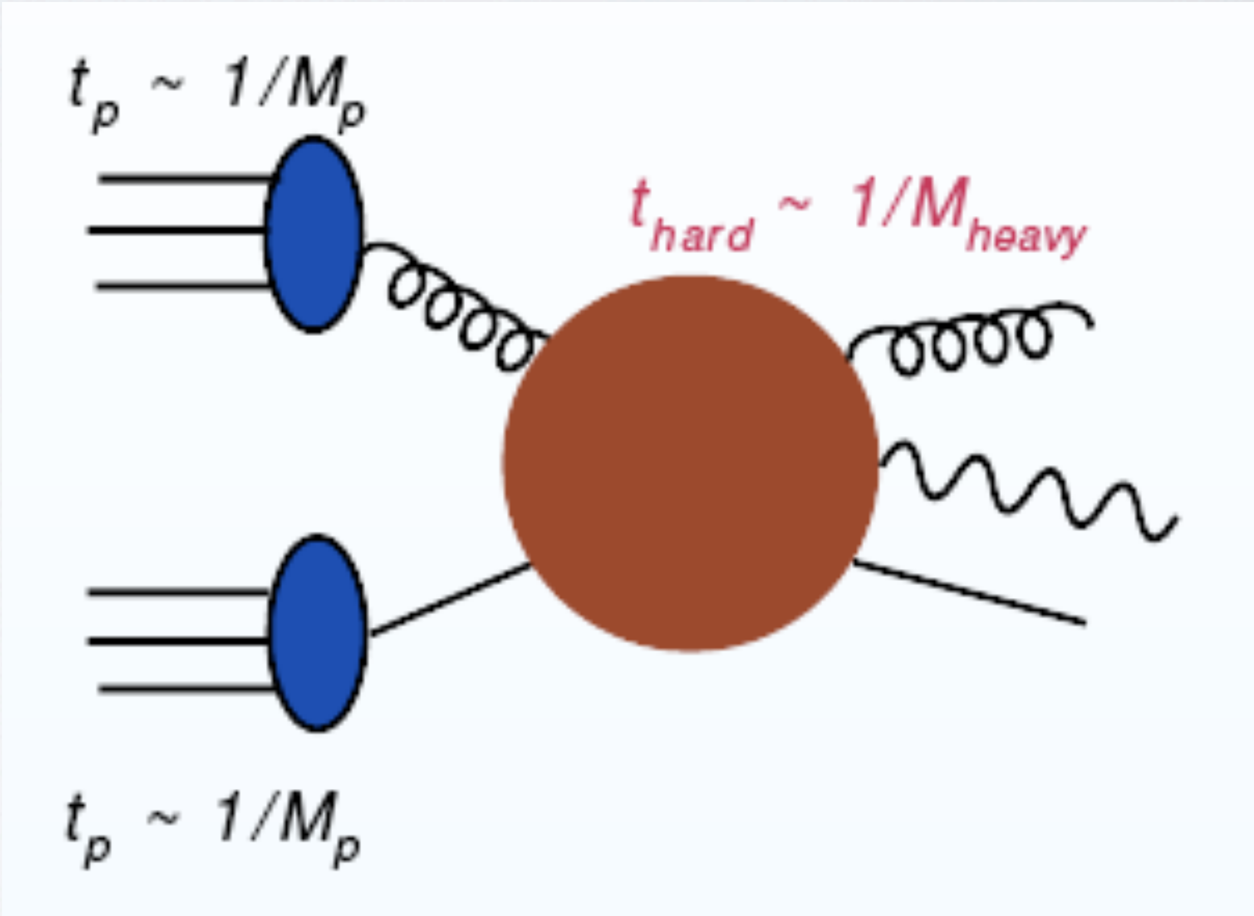
- Precision determination of fundamental mass and coupling parameters and parton densities.
- Quantitative predictions for complicated backgrounds to the signatures of novel particles and interaction
- Efficient searches for new physics signals
- Reliable elimination of theoretical new physics models
- "Coronation" of the new physics paradigm after the Standard Model
- Understanding of the inner workings of gauge theories

$$\mathrm{ROI} = \frac{\mathrm{Gain(Cost)} - \mathrm{Cost}}{\mathrm{Cost}}$$

FOUNDATIONS

QCD is a predictive theory

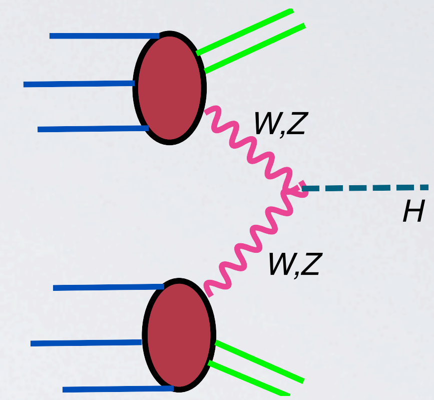
- Factorization
- Infrared Safety
- Perturbation theory
- (Global) experimental data



but not a solved theory!

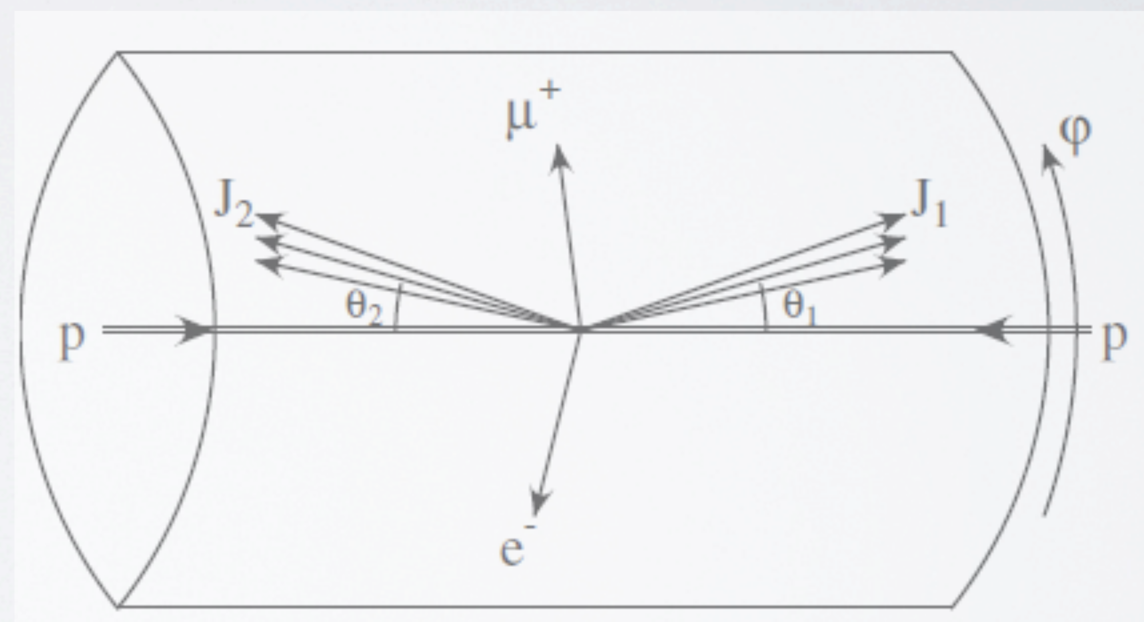
EXAMPLE: WEAK BOSON FUSION

- Characteristic topology with a pair of two forward jets.

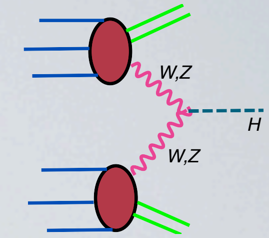


- Little color exchange in the t-channel, little amount of radiation from perturbative QCD in central detector regions

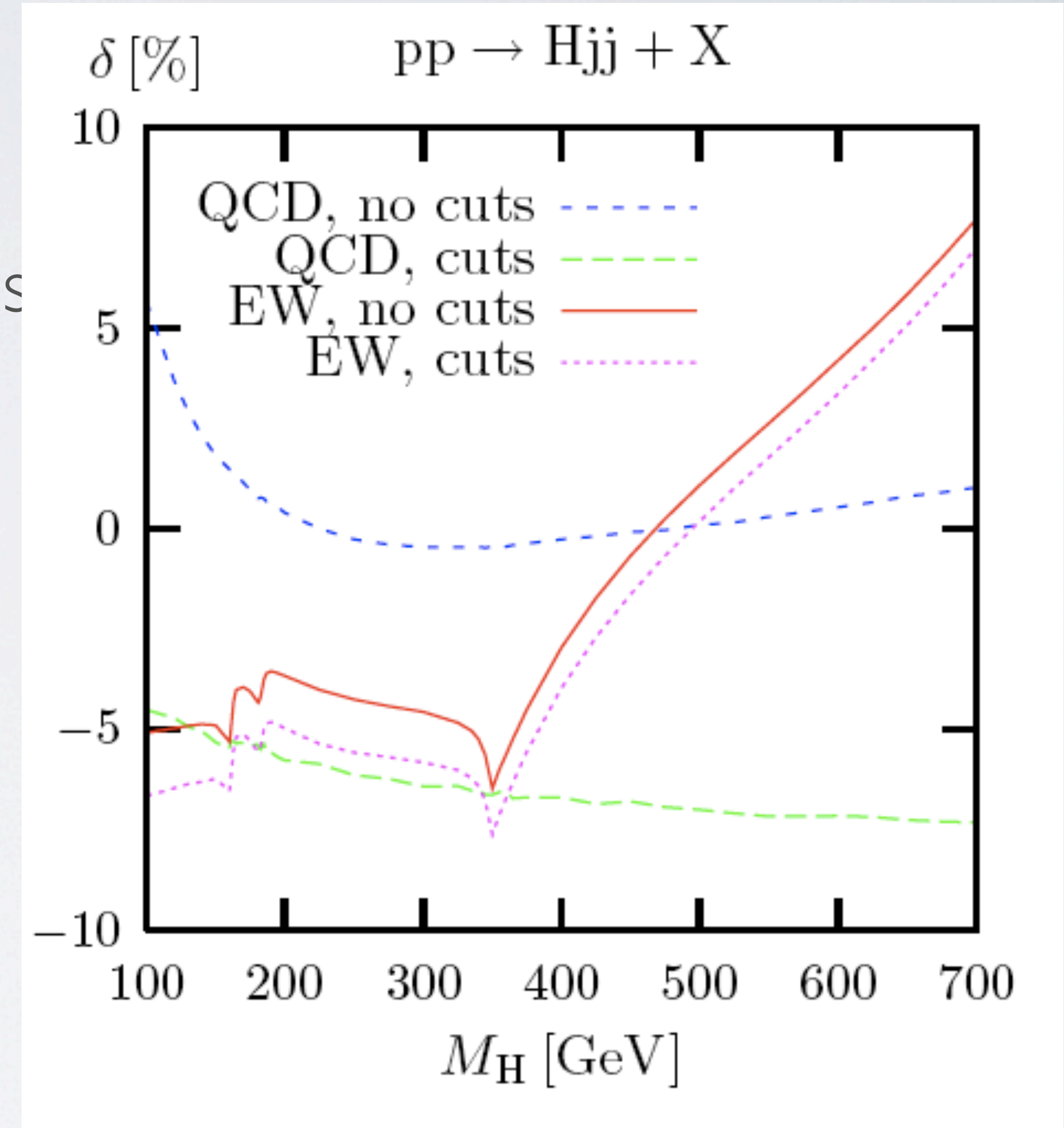
  (Rainwater,Zeppenfeld;Rainwater,Zeppenfeld,Hagiwara; Plehn, Rainwater, Zeppenfeld;...)



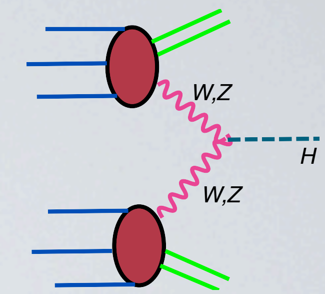
PERTURBATIVE EFFECTS



- NLO QCD (Han,Valencia,Willenbrock; Figy,Oleari,Zeppenfeld; Berger, Campbell)
- NLO QCD and electro-weak corrections (Ciccolini,Denner,Dittmaier)
- Signal-Background interference (Andersen,Binoth,Heinrich,Smillie)
- Gluon induced weak boson fusion (Harlander,Vollinga,Weber)
- Total cross-section in NNLO QCD and 2% estimated precision (Bolzoni,Maltoni,Moch,Zaro)



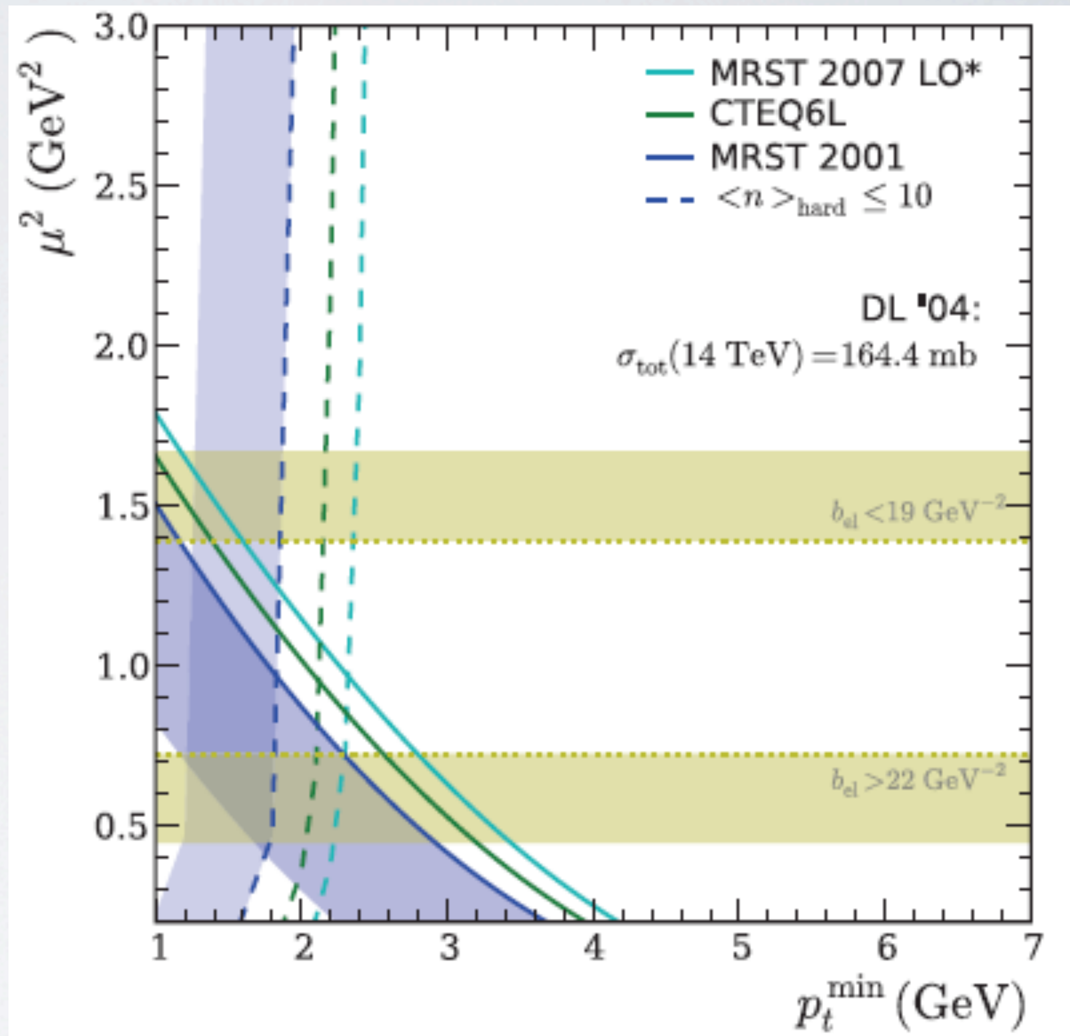
NON PERTURBATIVE QCD EFFECTS



- no central jets with Pt > 20 GeV, sensitive to the underlying event

- we shall need to revisit underlying-event models at the LHC (Baehr,Butterworth,Seymour; Baehr,Gieseke,Seymour; Dasgupta,Magnea,Salam;...)

- also, revisit jet-veto analysis after first (7 TeV) and second (14 TeV) LHC data.

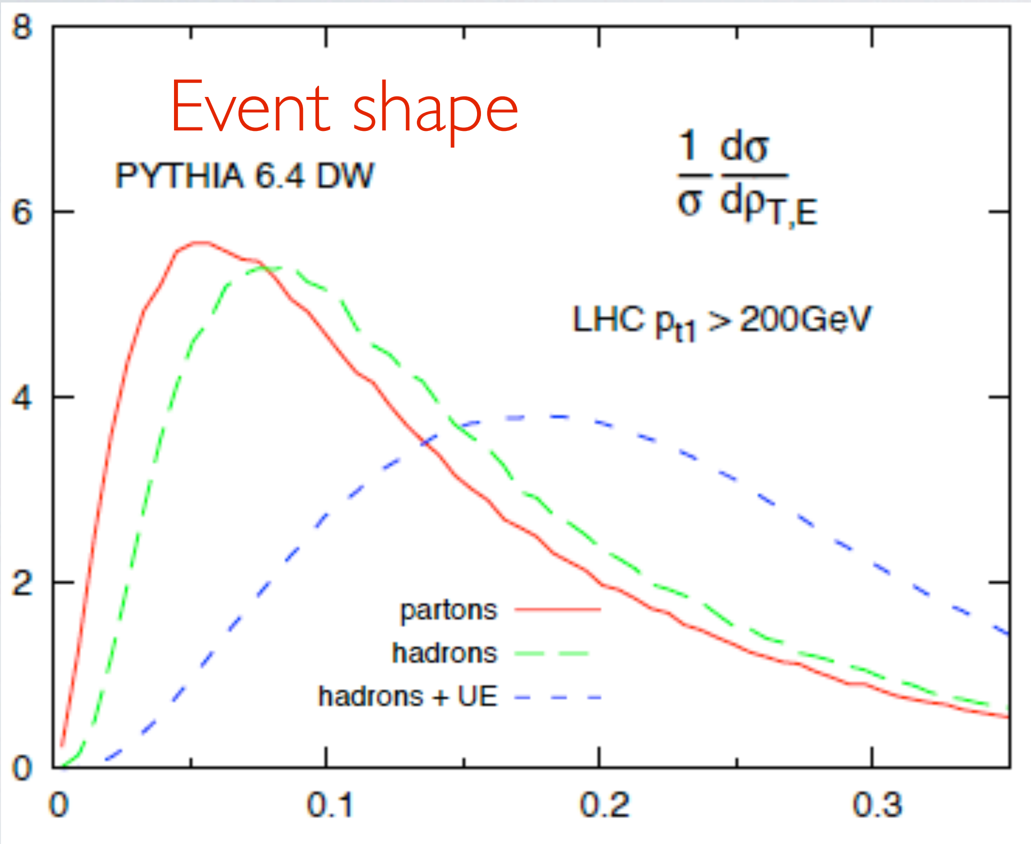


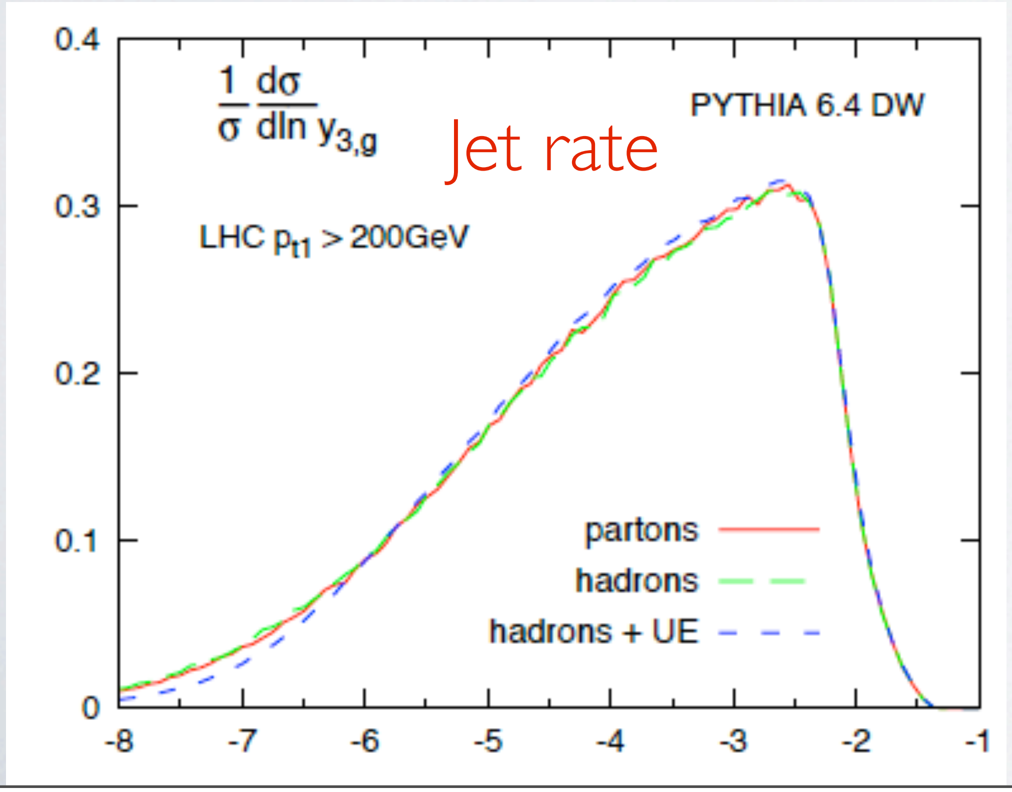
Baehr,Butterworth,Seymour: restrictions from LHC total cross-section on a eikonal model for the UE

ANALYZING THE MAKE OUT OF JETS

- Jets are rich in their topology.
- Contain information on their origin (QCD low or high-pt splittings, decays of colorful or colorless heavy particles, etc)
- Jet definitions and observables can be a powerful tool for LHC studies
- Event shapes probe the anatomy of QCD radiation.

EVENT SHAPES AT HADRON COLLIDERS AND NON-PERTURBATIVE EFFECTS





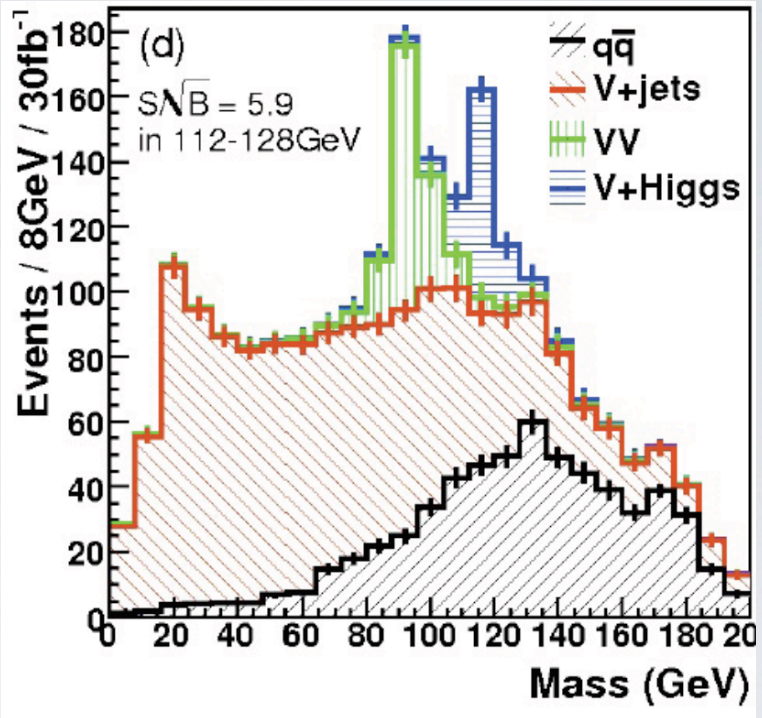
- Banfi,Salam,Zanderighi

- Jet resolution and event shape variables have different sensitivity to hadronization and underlying event

- Can be used to tune parton-shower Monte-Carlo's at the LHC.

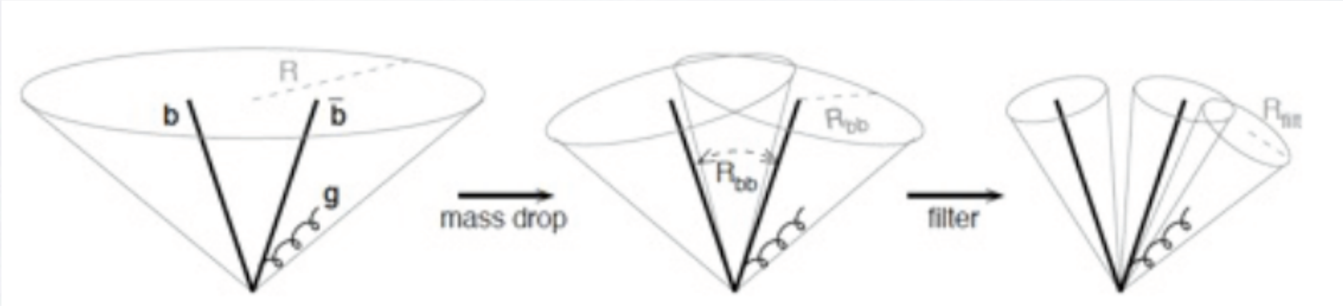
JET SUBSTRUCTURE

Butterworth, Davison, Rubin, Salam



- Check for events where the higgs and the vector boson are back-to-back

- cluster into fat jets. analyze their make up

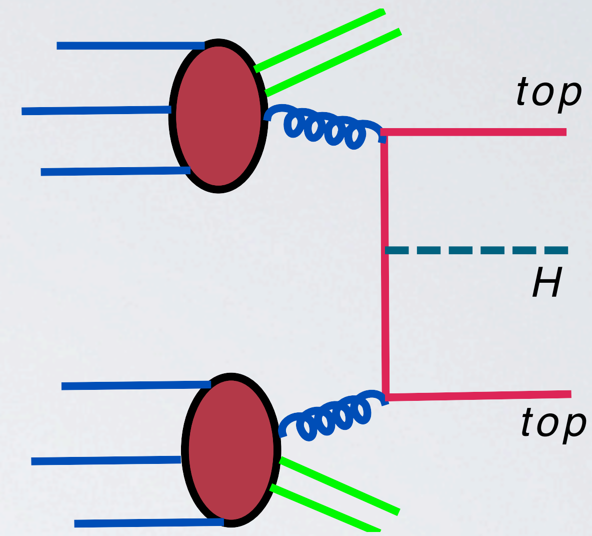


- two b-tagged smaller size jets with roughly same mass?

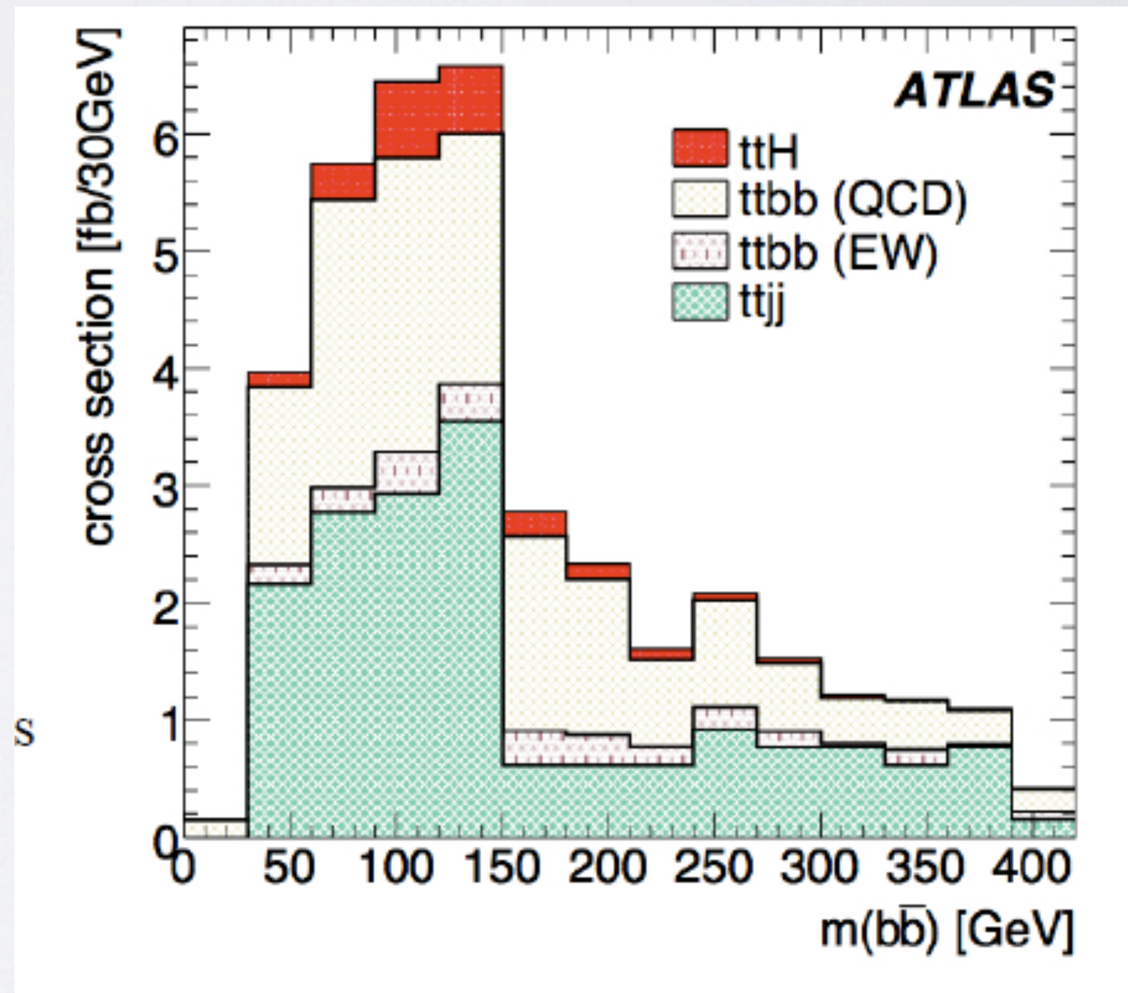
Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B \cdot \text{fb}}$
C/A, $R = 1.2$, MD-F	0.57	0.51	0.80
$K_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCone, $R = 0.8$	0.49	1.33	0.42

- filter underlying event with a smaller jet-size parameter (R)

ASSOCIATED WITH TOP

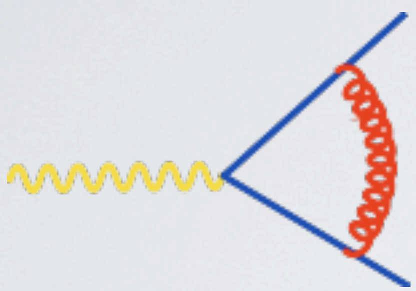
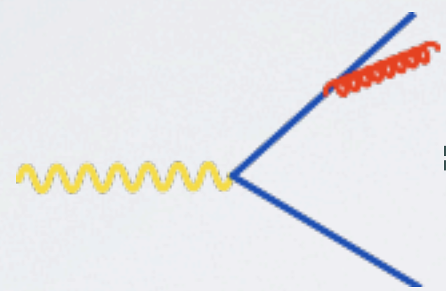


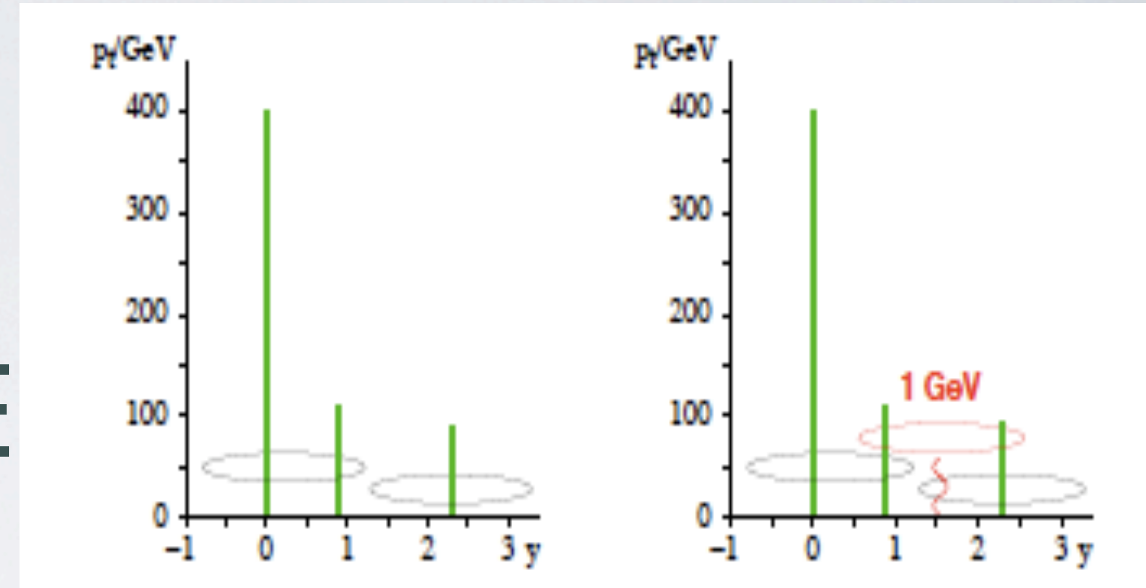
- Direct access to the top yukawa coupling
- Large backgrounds, difficult combinatorics (six jets)
- dropped out from the list of discovery channels
- can revive it with "jet tomography"



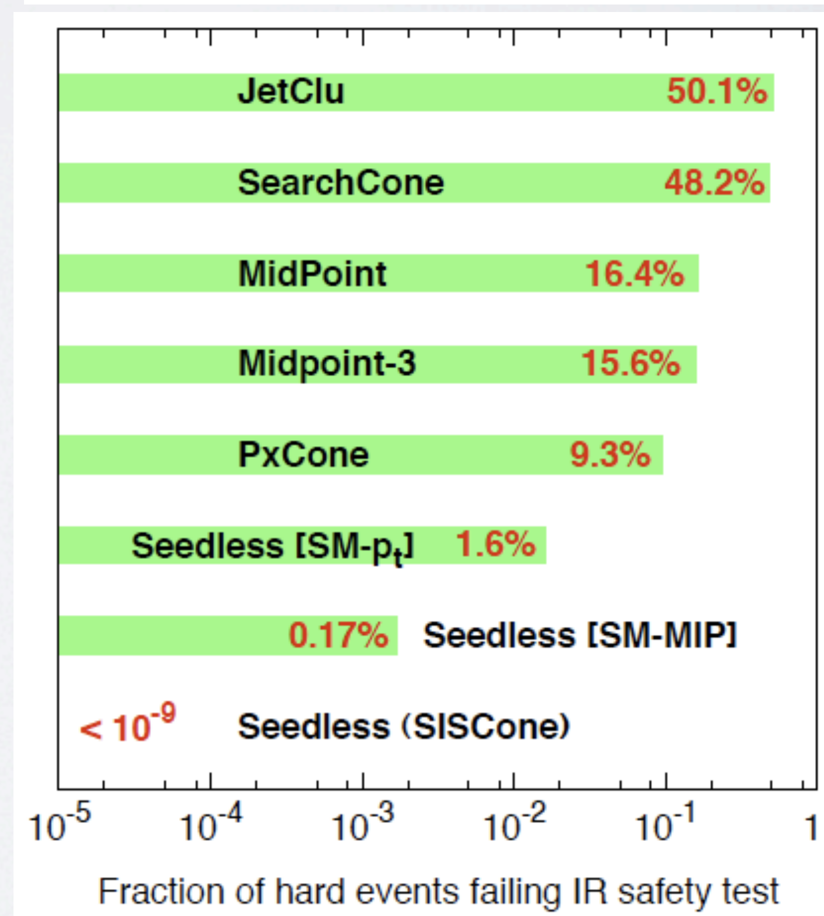
JETS AND INFRARED SAFETY

$-\infty + \infty$

 +  =FINITE



arXiv:0704.0292

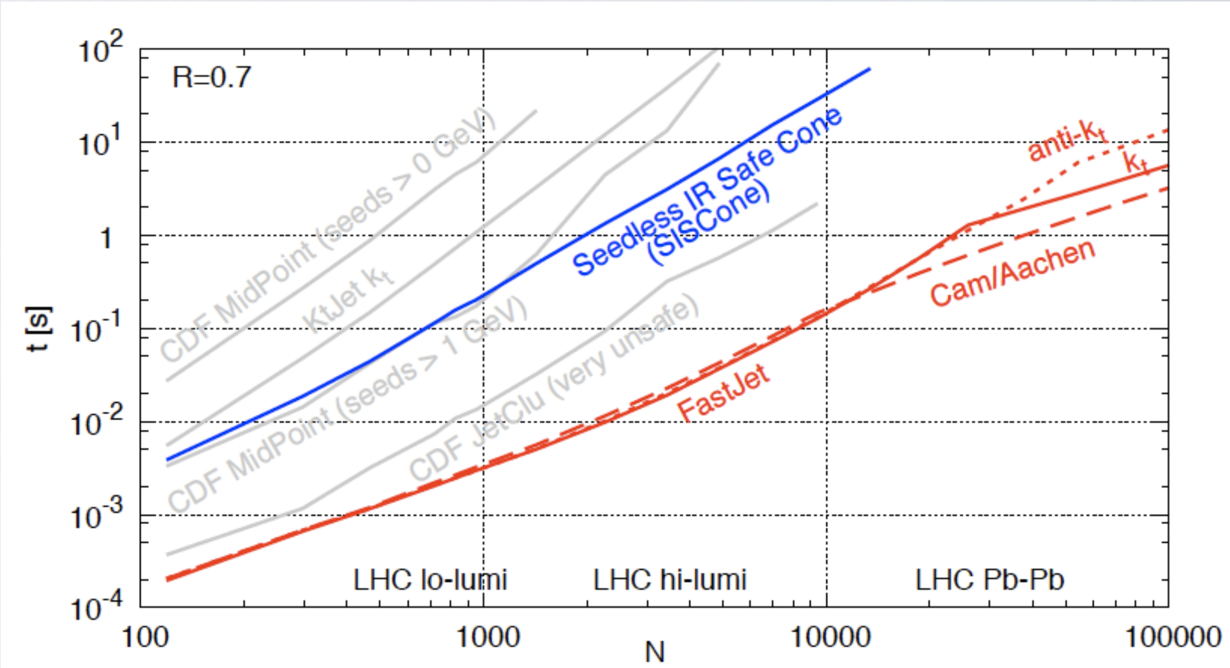


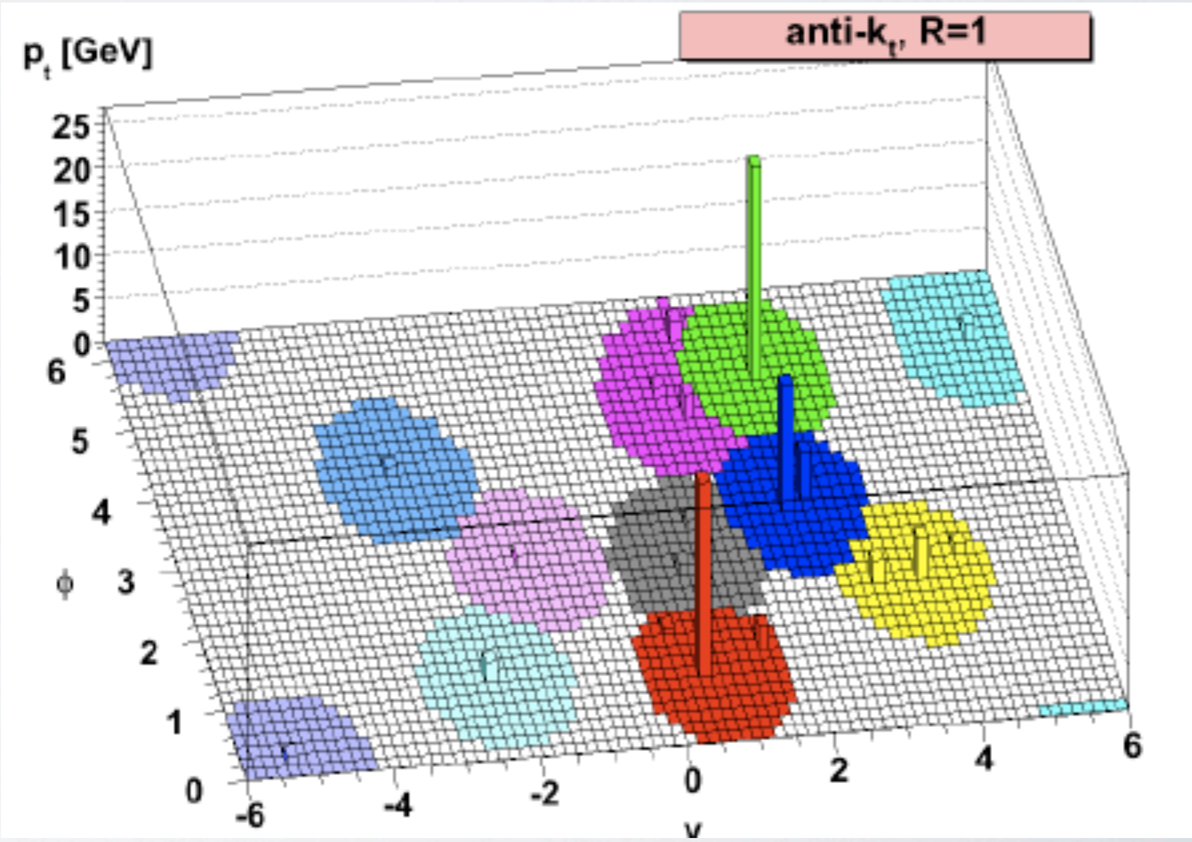
- Soft or Collinear parton emission must not alter the number of jets in an event.
- Many jet measurements are not directly comparable to perturbative calculations (e.g. W+3 jets with JETCLU @ NLO)
- infrared safe algorithms

FAST AND SAFE JET FINDING

Cacciari, Salam, Soyez (2007-2009)

- Fast implementation of recombination algorithms
- New infrared safe cone algorithm (SISCone)
- Better understanding of jet areas
- anti-Kt: recombination algorithm with "perfect cones"

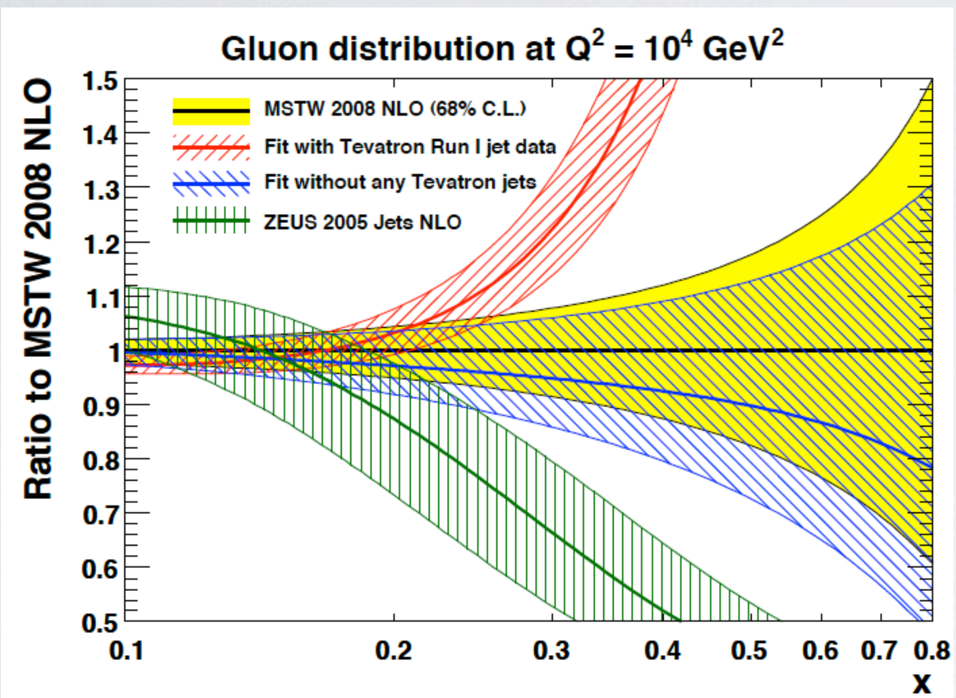




PARTON DENSITIES

- Several efforts for a precise determination of parton densities:
CTEQ: Pumplin, Huston, Lai, Nadolsky, Tung, Yuan(NLO, global fit);
MSTW: Martin,Stirtling,Thorne,Watt (NNLO, global fit);
JR: Jimenez-Delgado,Reya (NNLO, DIS fit);
ABKM: Alehkin,Bluemlein,Klein,Moch (NNLO, DIS and Drell-Yan fit);
HERA colloborations (NNLO, DIS fit)
- Input for precise hadron collider phenomenology.
- New ideas on pdf extraction, using Artificial Neural Network methods (Ball, Del Debbio, Forte, Guffanti, Latorre, Piccione, Rojo, Ubialli)
- Improvements on theoretical treatment, better error estimation, but also important changes from older sets

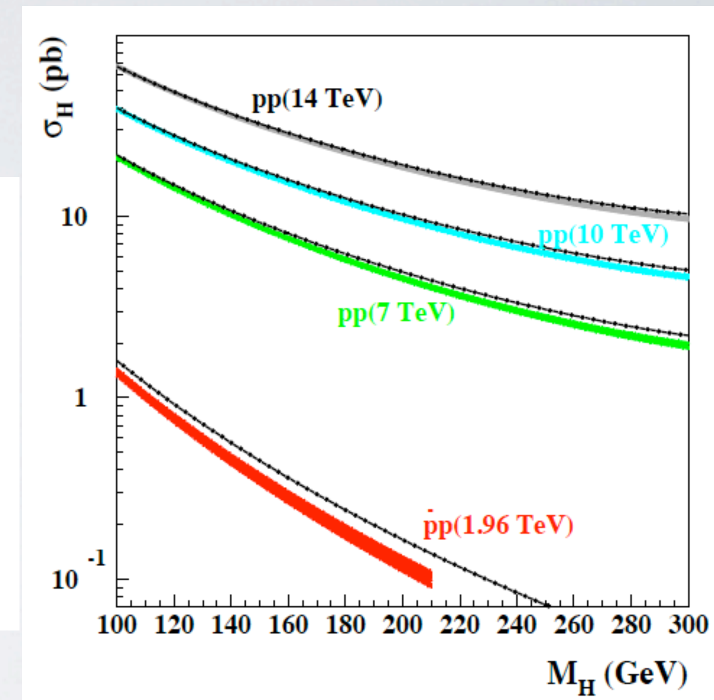
IMPORTANT PDF DIFFERENCES



MSTW high-x gluon density, impact of Tevatron jet measurements

$\sqrt{s}$ (TeV)	ABKM	MSTW2008
1.96 ($\bar{p}p$)	6.91 ± 0.17	7.04
7 (pp)	131.3 ± 7.5	160.5
10 (pp)	343 ± 15	403
14 (pp)	780 ± 28	887

MSTW vs ABKM for top pair cross-section



MSTW vs ABKM for Higgs cross-section

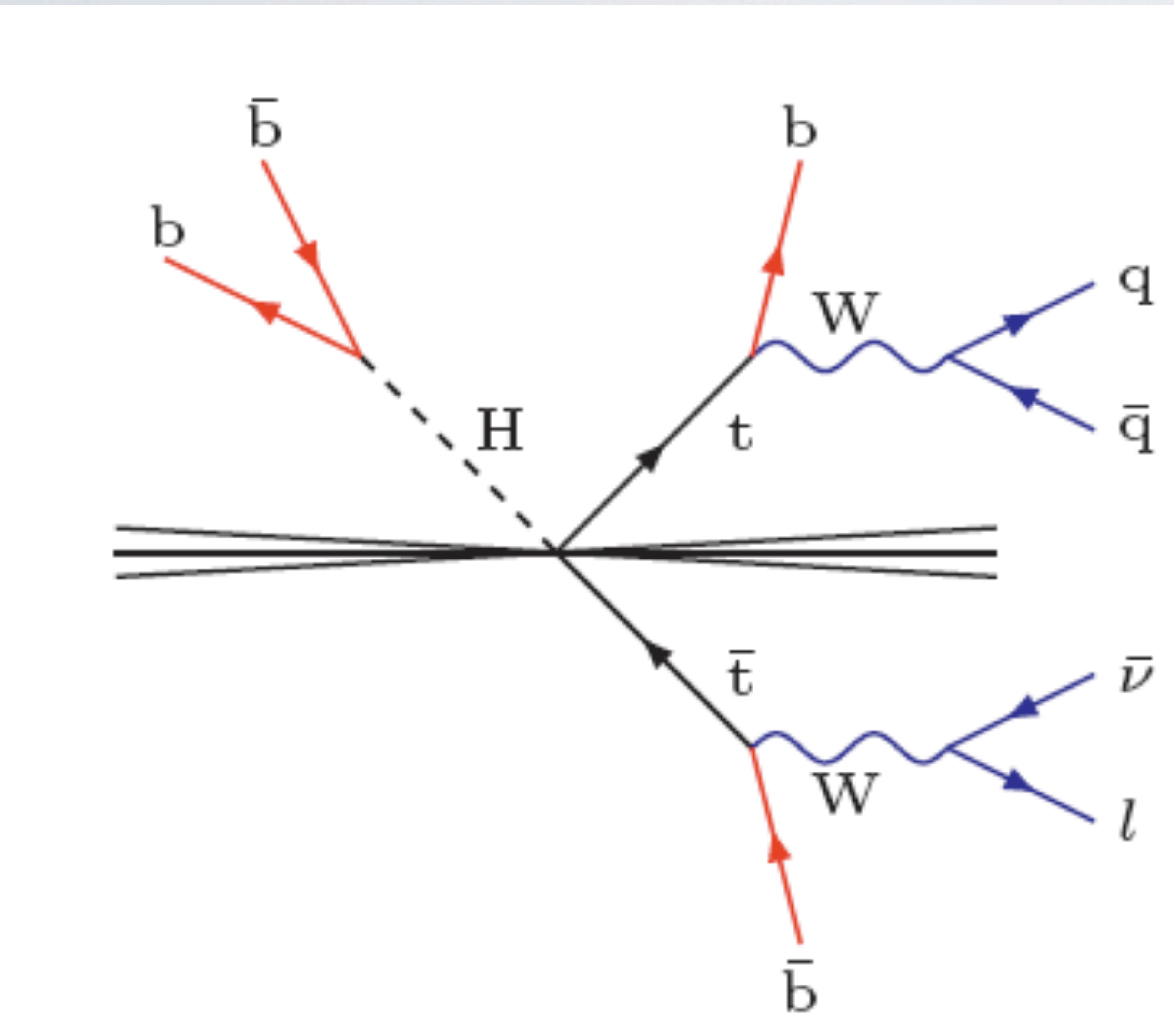
MRST 2001	MRST 2004	MRST 2006	MSTW 2008
0.3833	0.3988	0.3943	0.3444

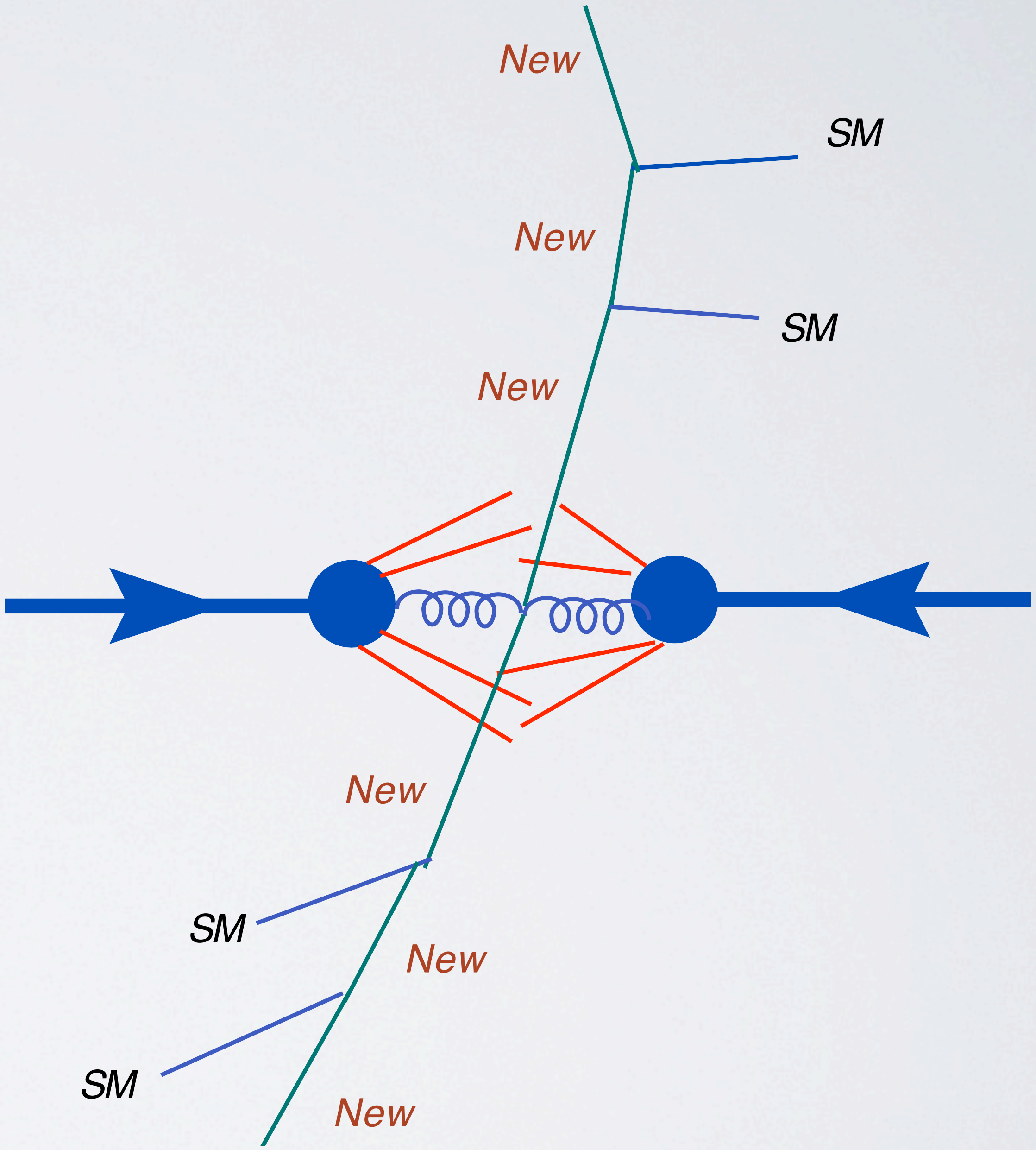
Higgs cross-section at the TEVATRON MSTW vs MRST

LHC data and QCD theory will be very useful to constrain pdfs

A difficult case: high-x gluon densities

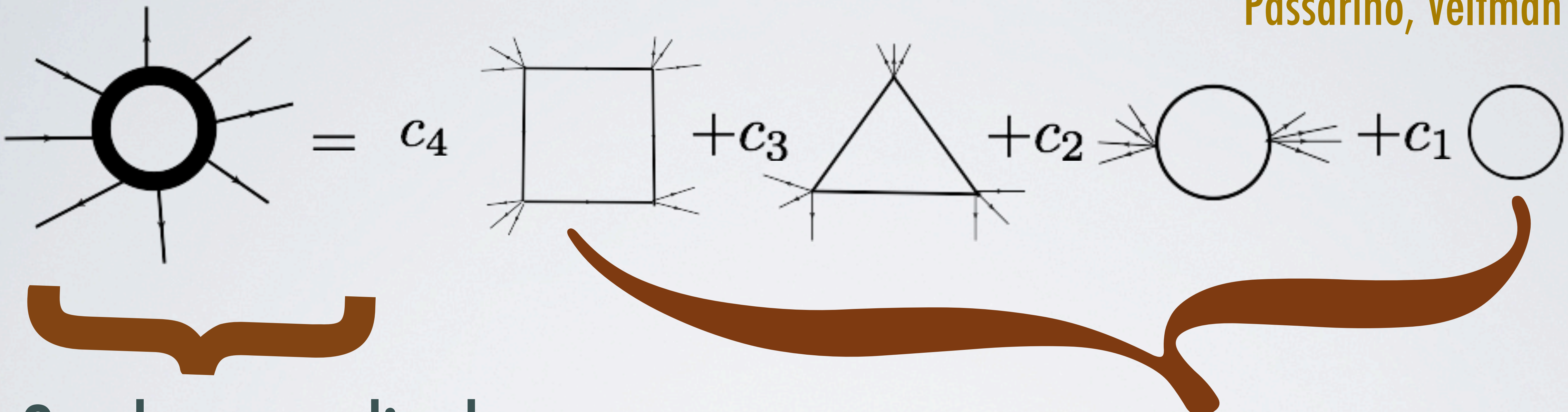
NEW PHYSICS APPETITE FOR COMPLICATED QCD SIMULATIONS





MASTER INTEGRALS

Passarino, Veltman *1980s*



One-loop amplitude in Gauge theory

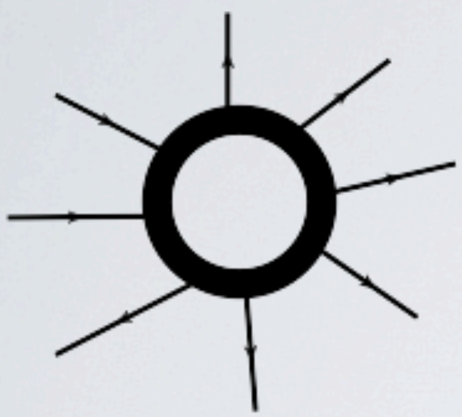
Integrals in scalar field theory

Known method(s) to compute a,b,c,d coefficients had a (# Legs)! computational cost

UNITARITY: A VISIONARY IDEA

Bern, Dixon, Dunbar, Kosower *1990s*

$Tree \times Tree$



$$\approx \int \frac{d^d k}{k^2 (k+p)^2}$$

- Trees as input for the integrand
- Manifest gauge invariance cancelations
- Simplifications by using "natural" spinor variables

- Mismatch between Trees in four dimensions and loop integration in D-dimensions
- Introduction of four dimensional helicity regularization scheme
- Clever theory input (collinear factorization) to recover the full one-loop amplitude

Trees were an essential ingredient. No explicit connection of master integral coefficients to tree amplitudes.

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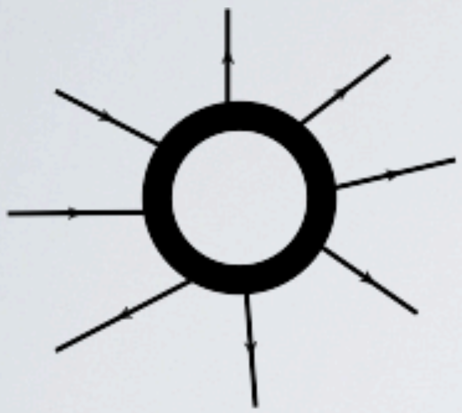

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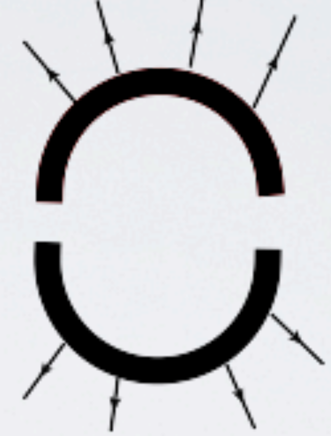

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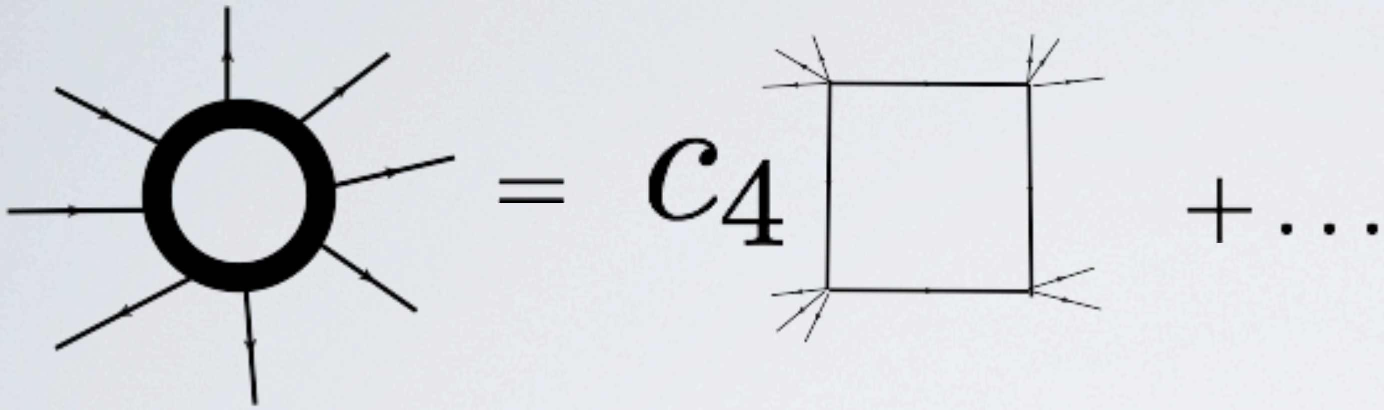
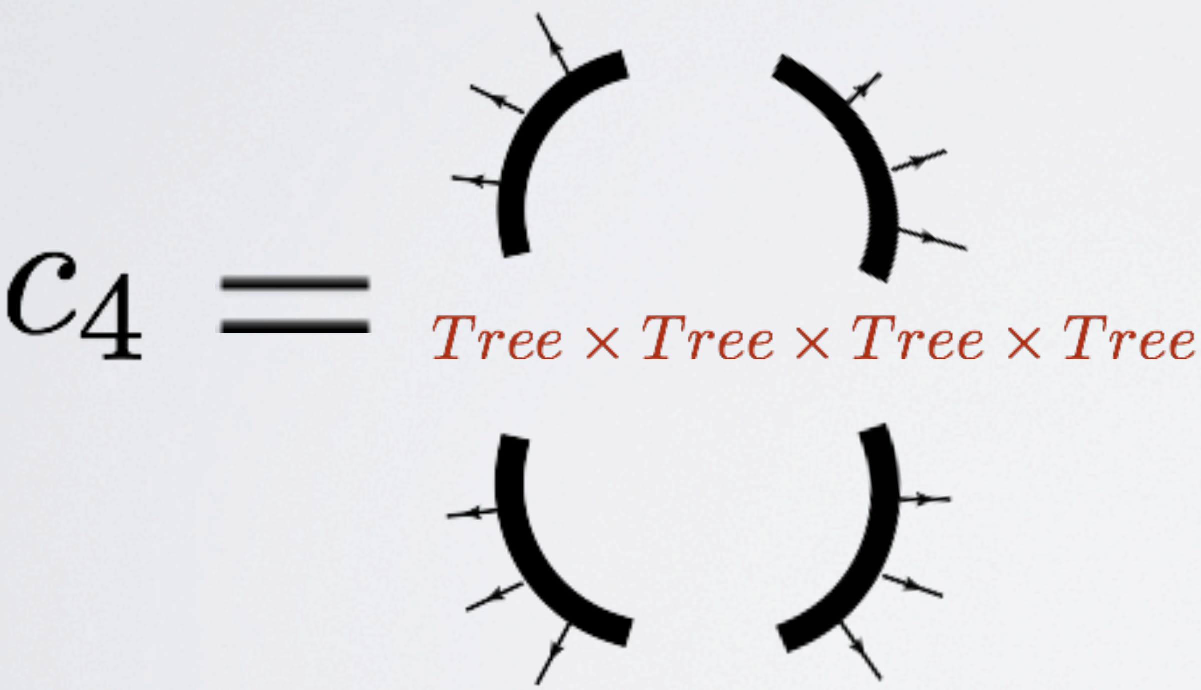
COEFFICIENT OF BOX MASTER

Britto, Cachazo, Feng 2004



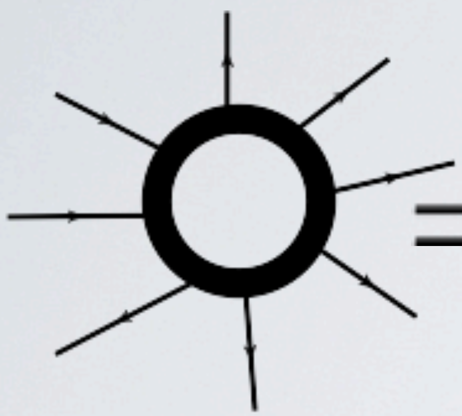


- Simple product of four tree amplitudes
- Evaluated at complex momenta
- corresponding to loop momentum values where all propagators of the box master integral are ON-SHELL

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006

(building on del Aguila, Pittau, 2004)



$$= \int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

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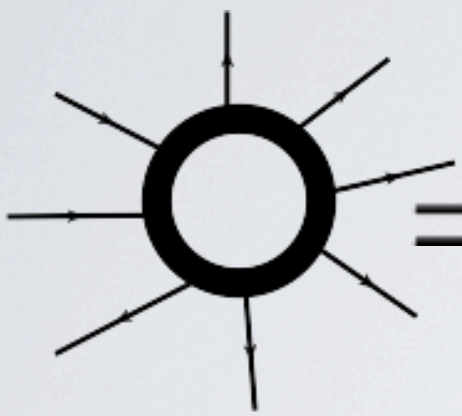

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$$\cancel{+\tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k})} \Big]$$

After Integration:

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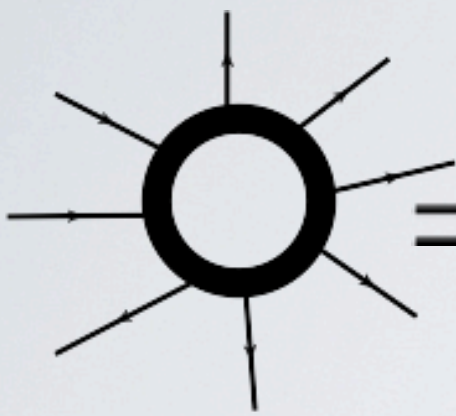

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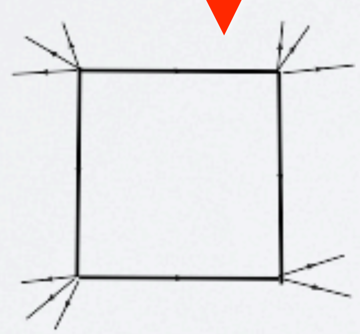
After Integration:

$$= c_4$$



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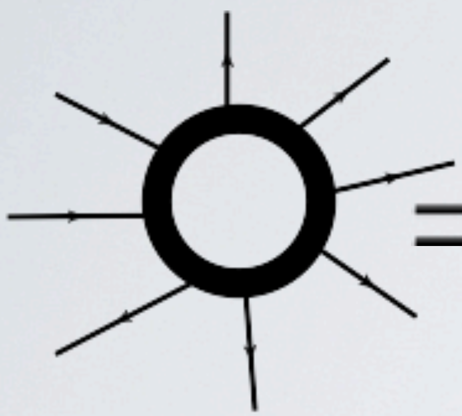

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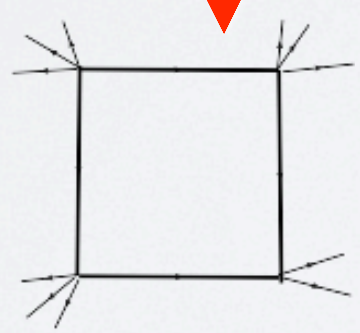
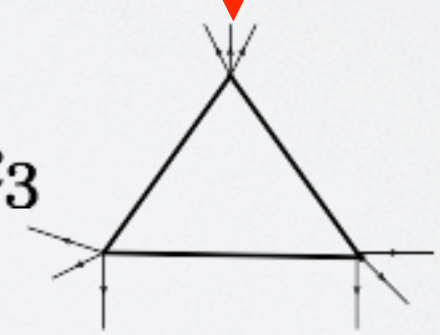
$= \; c_4$  $+c_3$ 

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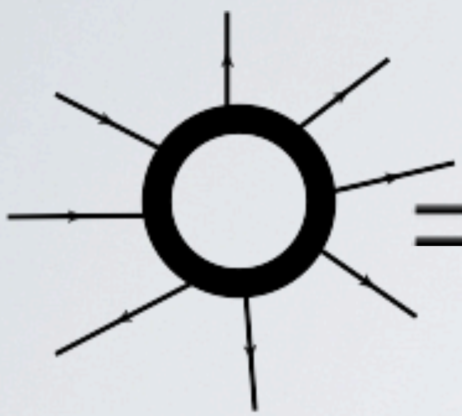

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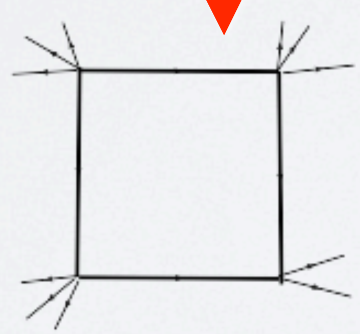
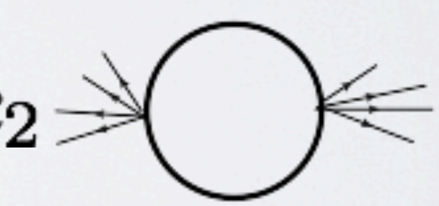
$= \; c_4$  $+c_3$  $+c_2$ 

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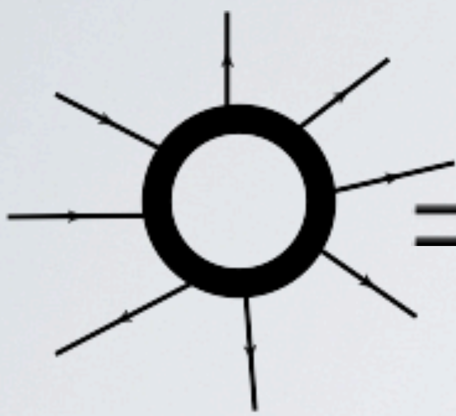

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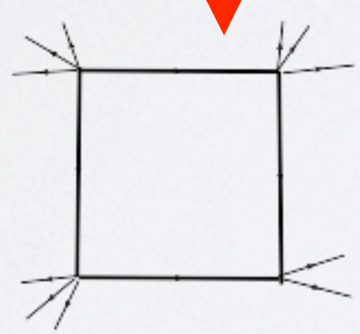
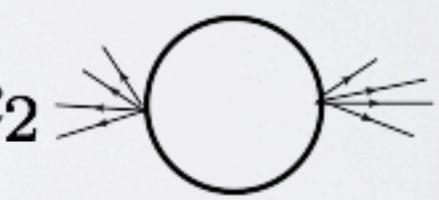
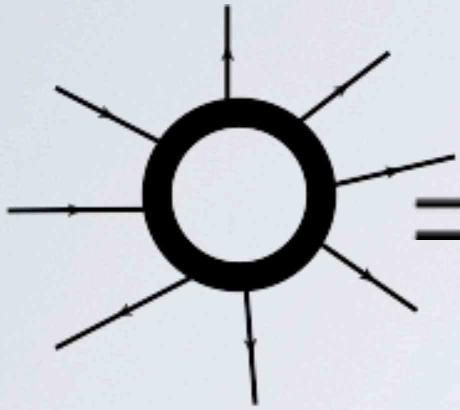
$= c_4$  $+c_3$  $+c_2$  $+c_1$ 

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006



$$= \int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

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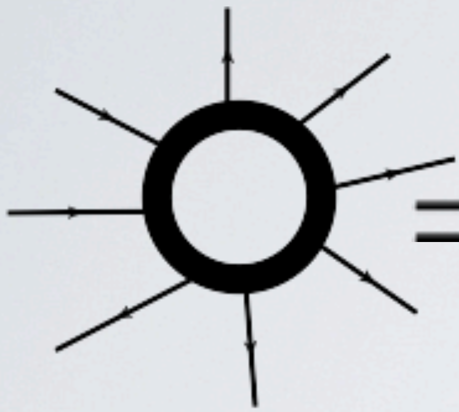

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$\tilde{f}_i(\vec{k}), f_i(\vec{k})$: Known rational functions of the loop momentum

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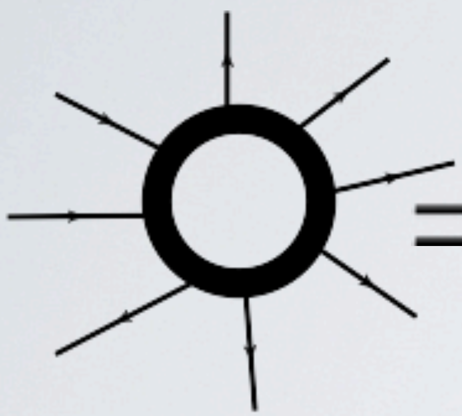
Ossola, Papadopoulos, Pittau 2006



$$= \int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

$\tilde{f}_i(\vec{k}), f_i(\vec{k})$: Known rational functions of the loop momentum

$\tilde{c}_i, c_i$: coefficients can be determined algebraically computing the integrand at a sufficient number of values for $\vec{k}$

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006

$$\int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

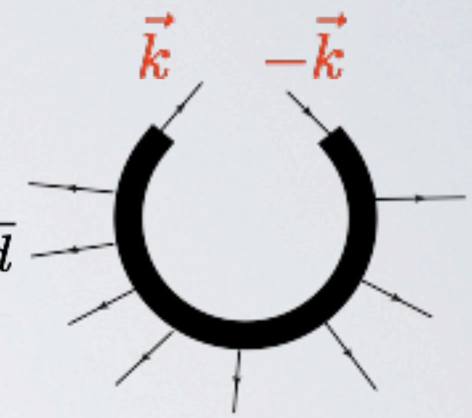
$$+\tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006

$$\int \frac{d^dk}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+\tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big] = \int \frac{d^dk}{(2\pi)^d}$$

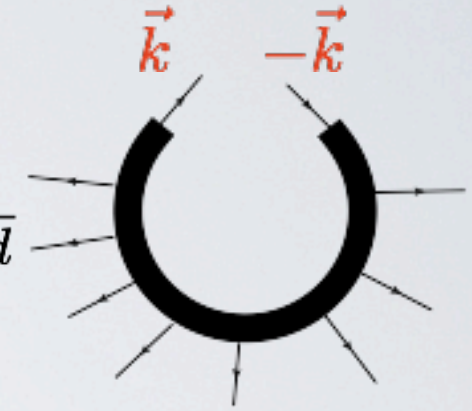


- Integrand is "easy", essentially a tree amplitude

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006

$$\int \frac{d^dk}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k}) + \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big] = \int \frac{d^dk}{(2\pi)^d}$$



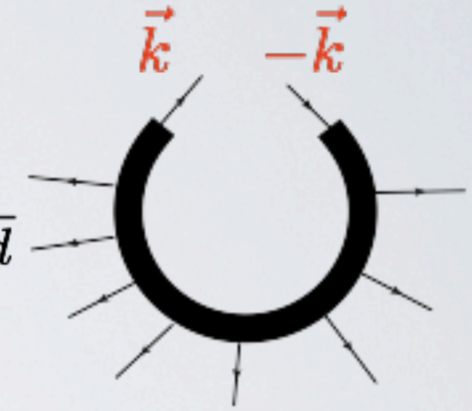
- Integrand is "easy", essentially a tree amplitude

Evaluate integrand at loop momenta values such as loop particles are set ON SHELL

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau 2006

$$\int \frac{d^dk}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k}) + \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big] = \int \frac{d^dk}{(2\pi)^d}$$



- Integrand is "easy", essentially a tree amplitude

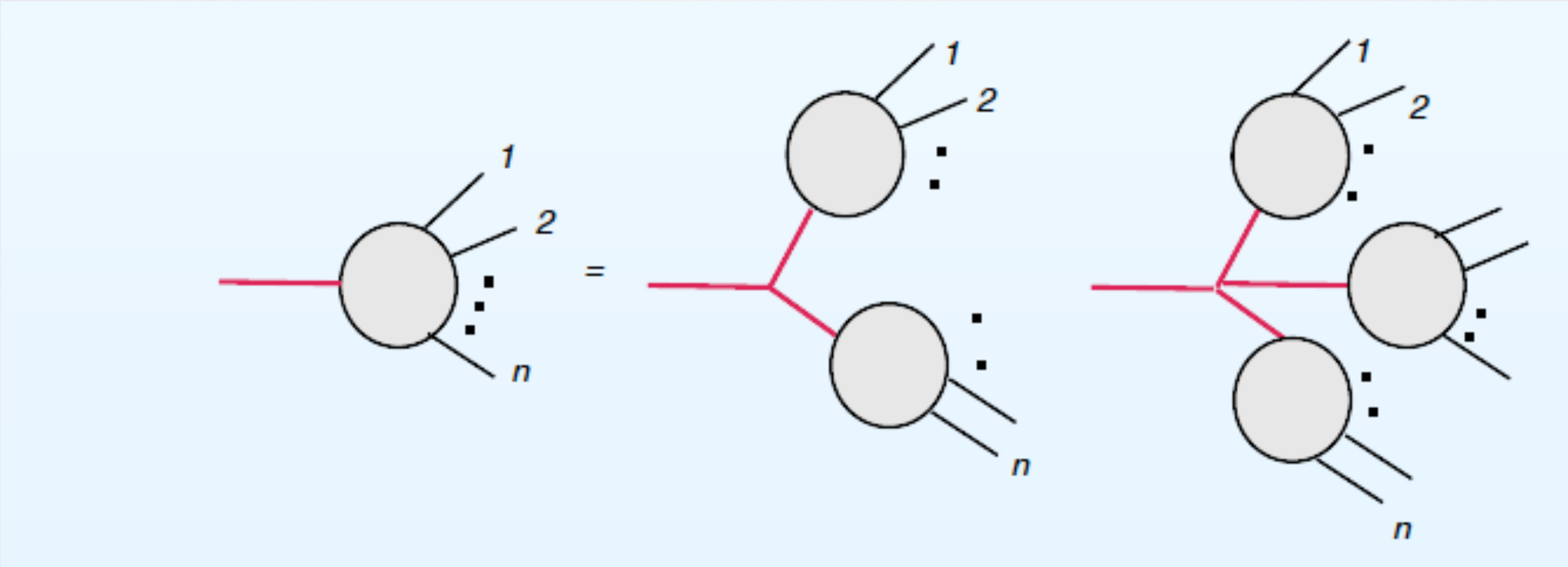
Evaluate integrand at loop momenta values such as loop particles are set ON SHELL

- ON-SHELL: determines coefficients successively

COEFFICIENTS AS TREE PRODUCTS

Ellis, Giele, Kunszt 2007

- ON-SHELL loop propagators = Product of tree amplitudes
- Evaluation of trees with powerful recursive methods



e.g. Berends-Giele, Britto-Cachazo-Feng-Witten, etc

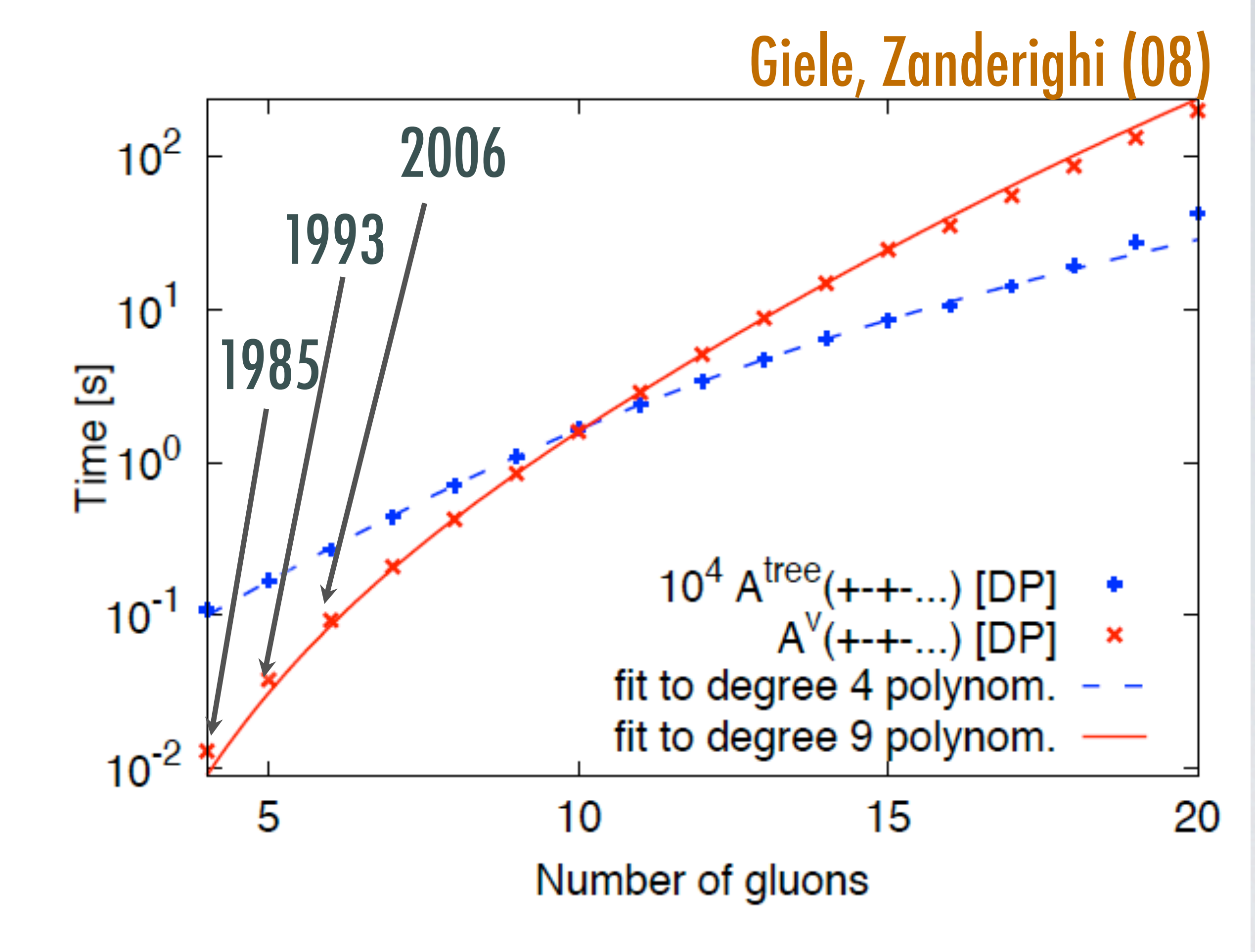
CONFLICT OF DIMENSIONS

Loop Integrations in D dimensions, Tree amplitudes in four dimensions. Mismatch, i.e. missing terms from amplitude evaluation. Requires a second calculation.

- Specialized tree-like recursions in D=4 for the missing terms
  Berger, Bern, Dixon, Forde, Kosower 2006
- Elegant/general solution: Amplitude in a general dimension from results in D=5 and D=6. Ellis, Giele, Kunszt, Melnikov 2008
- Specialized Feynman rules for missing terms:
  Draggiotis, Garzelli, Papadopoulos, Pittau 2009

BREATHTAKING DEVELOPMENTS

- One-loop amplitudes with 22 gluons Giele, Zanderighi (08); Lazopoulos (08); Giele, Winter (09)



- numerical evaluation of all 2 to 4 amplitudes in the Les-Houches 2007 wish-list

van Hameren, Papadopoulos, Pittau (09)

$$q\bar{q}, gg \to t\bar{t}b\bar{b}, b\bar{b}b\bar{b}, W^+W^-b\bar{b}, t\bar{t}gg$$

$$q\bar{q}' \to Wggg, Zggg$$

NLO CALCULATIONS @ LHC

- What can we hope for?
- We cannot do better than tree calculations..., i.e. processes with 7 or 8 particles in the final state.
- All 2 to 4 processes with both Feynman diagrammatic and unitarity methods
- 2 to 5 and perhaps 2 to 6 processes with unitarity methods

(2 TO 4) HADRON COLLIDER PROCESSES

$$pp \to t\bar{t}b\bar{b}$$

Bredenstein, Denner, Dittmaier, Pozzorini

Bevilacqua, Czakon, Papadopoulos, Worek

$$pp \to t\bar{t}jj$$

Bevilacqua, Czakon, Papadopoulos, Worek

$$pp \to W^{\pm} + 3jets$$

Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

Ellis, Kunszt, Melnikov, Zanderighi

$$pp \to Z + 3jets$$

Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

$$pp \to W + 4jets \text{ (first results)}$$

Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

LESSONS FROM MULTILEG NLO CALCULATIONS

- Guessing higher order corrections for multi-particle background processes without explicit calculations is hopeless
- There exists no unique "K-factor " across the full phase-space for processes with such complicated dynamics
- NLO computations can be used to optimize LO Monte-Carlo's

SUSY BACKGROUND

$$pp \to W(\to \tau\nu) + 3jets$$

ATLAS CUTS: $\sigma_{NLO} \simeq 200\% \sigma_{LO}$

CMS CUTS: $\sigma_{NLO} \simeq 110\% \sigma_{LO}$

Melnikov, Zanderighi

e.g. local scale for alphas in each branching

THE NNLO FRONT

- Precision of measurements at collider experiments is often excellent
- Perturbation theory is often slow at work, first correction after the leading order too large and too uncertain.
- All “2 to 1” and “2 to 2” hadron collider processes must be computed at NNLO.
- LEP, HERA, TEVATRON, LHC data = NNLO phenomenology

THREE-JET EVENTS FROM LEP

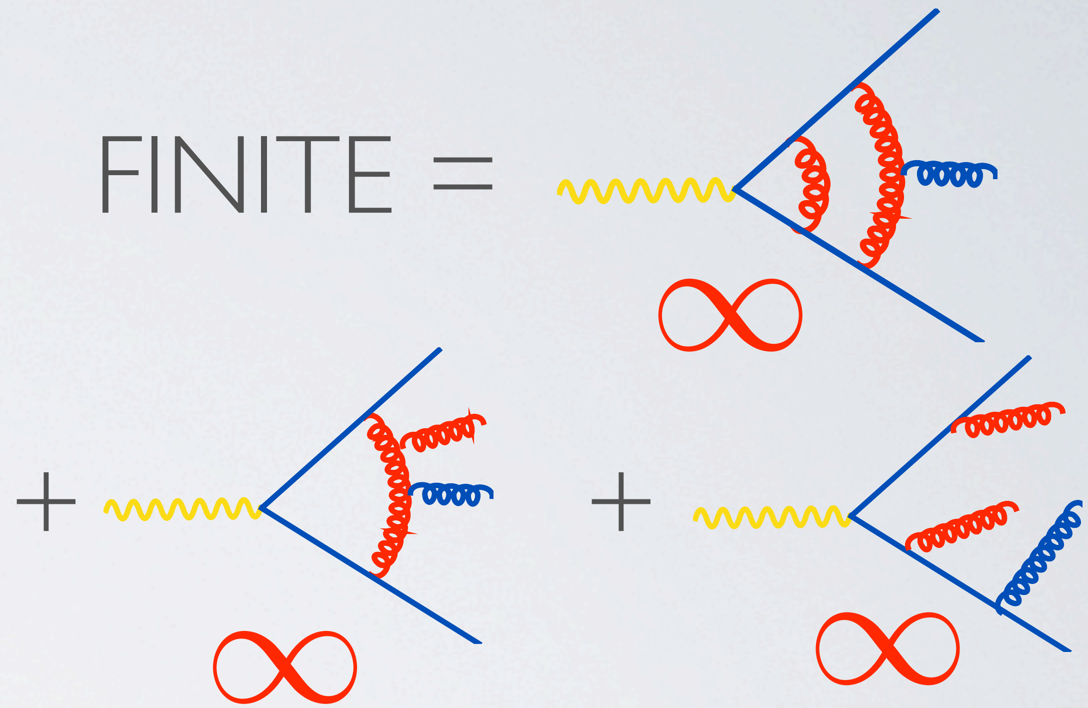
- LEP Legacy: Excellent measurements of three jet cross-sections and jet event shapes at various energies.
- Precise extraction of the strong coupling constant; largest error from theoretical prediction of the cross-section.
- NNLO corrections to $e^+e^- \to 3jets$ was the holy grail of the QCD community for more than a decade.

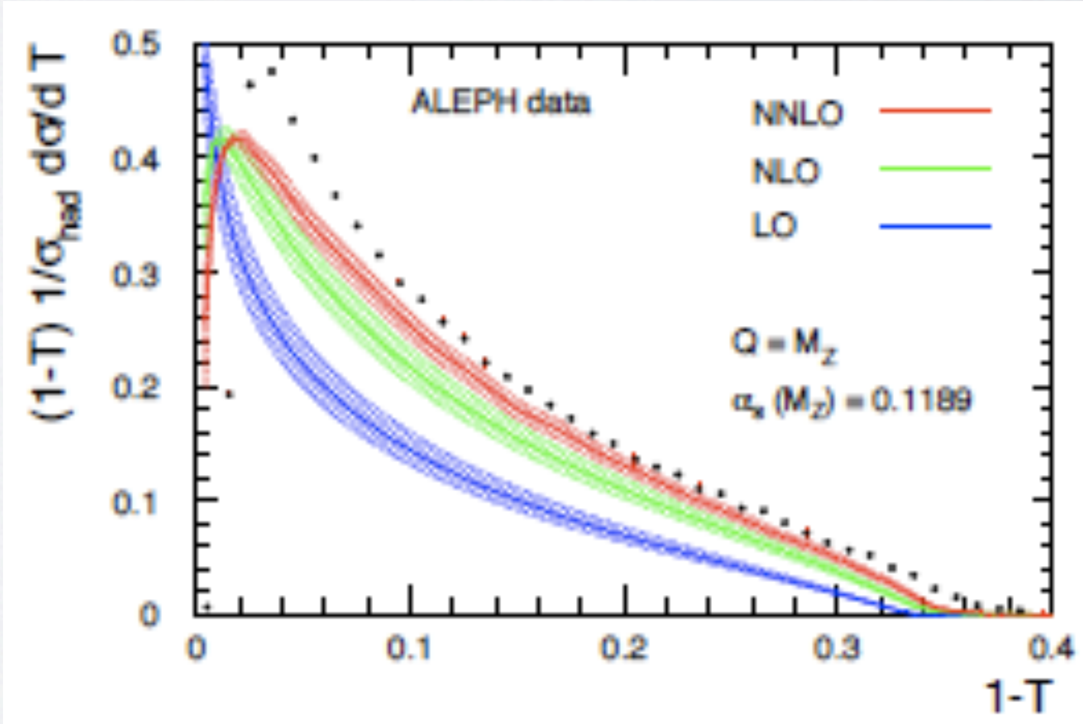
CANCELATION OF SINGULARITIES

- Two-loop amplitude computed already in 2001 by Garland, Gehrmann, Glover, Koukoutsakis, Remiddi

- A universal method for the cancelation of matrix element singularities through NNLO for lepton collider processes by Gehrmann-de Ridder, Gehrmann, Glover, Heinrich (2007)

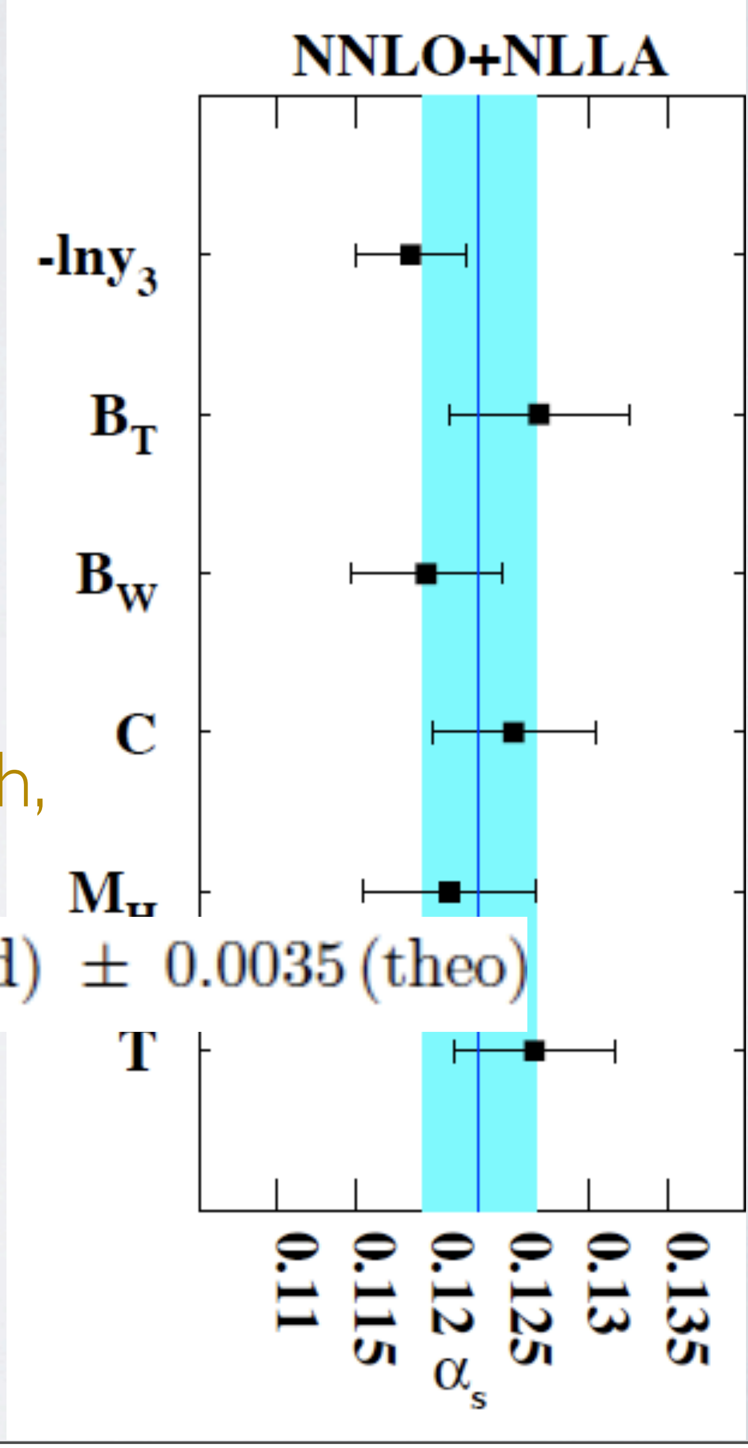
- Revision by Weinzierl (2008).





α_s FROM JET EVENT SHAPES

arXiv:0906.3436



- A synthesis of fixed order QCD, Electroweak corrections , resummation, and hadronization effects describe excellently three jet events at LEP.

- State of the art extraction of alphas with the NNLO result + NLL resummation

Dissertori, Gehrmann-de Ridder, Gehrmann, Glover, Heinrich, Luisoni, Stenzel

$$\alpha_s(M_Z) = 0.1224 \pm 0.0009\,(\mathrm{stat}) \pm 0.0009\,(\mathrm{exp}) \pm 0.0012\,(\mathrm{had}) \pm 0.0035\,(\mathrm{theo})$$

- also from NNLO+"SCET resummation" of the thrust distribution (Becher,Schwarz).

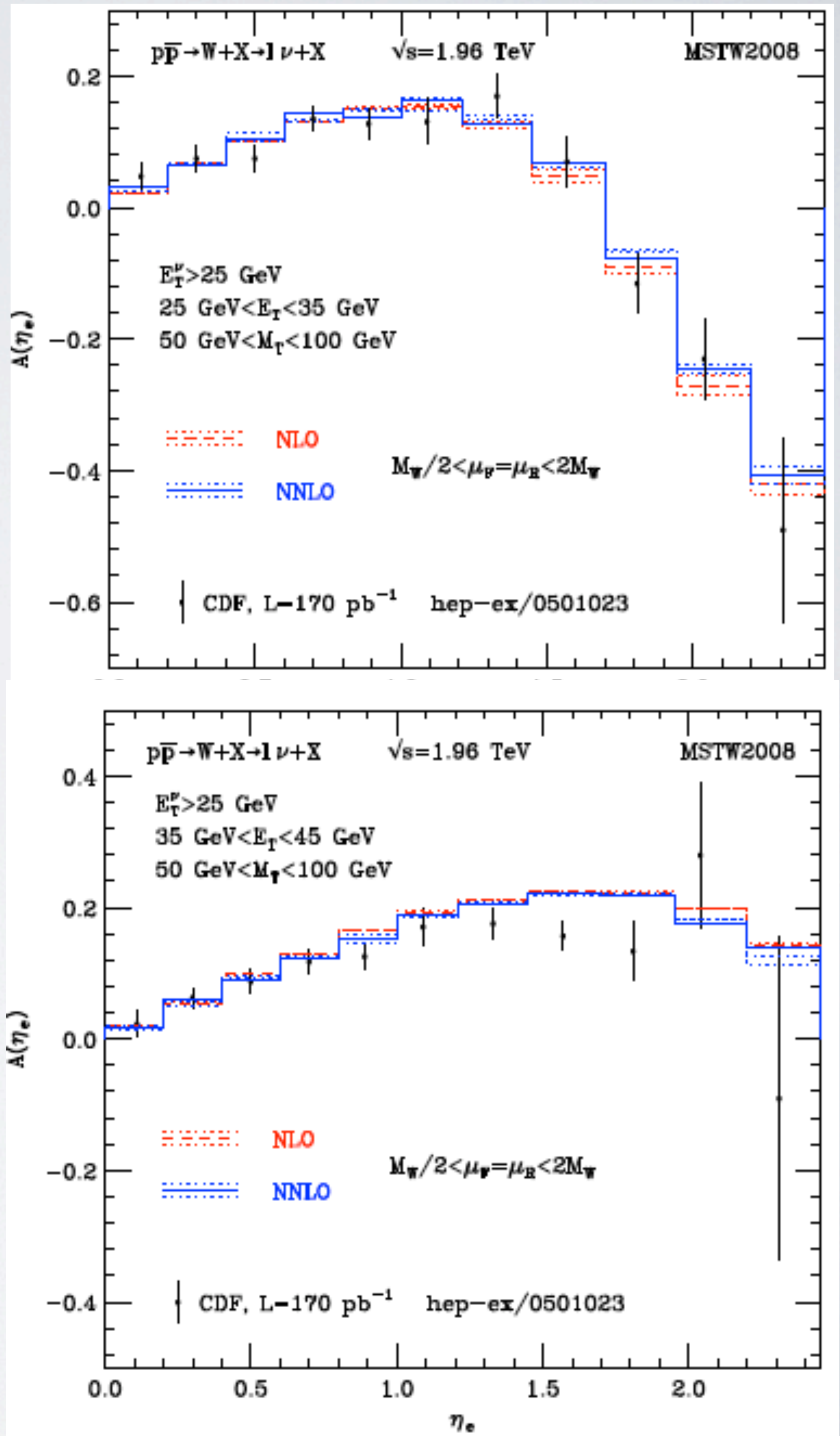
DRELL-YAN THEORY

- NNLO total cross-section
  Hamberg, van Neerven (1990);
  Harlander, Kilgore (2002)

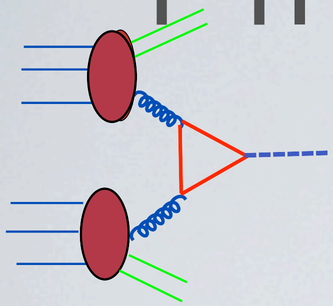
- NNLO rapidity distribution
  CA,Dixon,Menikov,Petriello (2004)

- Fully differential NNLO
  Melnikov,Petriello (2006);
  Catani, Cieri,Ferrera,Grazzini (2009)

- Recent application, lepton charge asymmetry
  Catani,Ferrera,Grazzini (2010)



HIGGS PRODUCTION AT NNLO

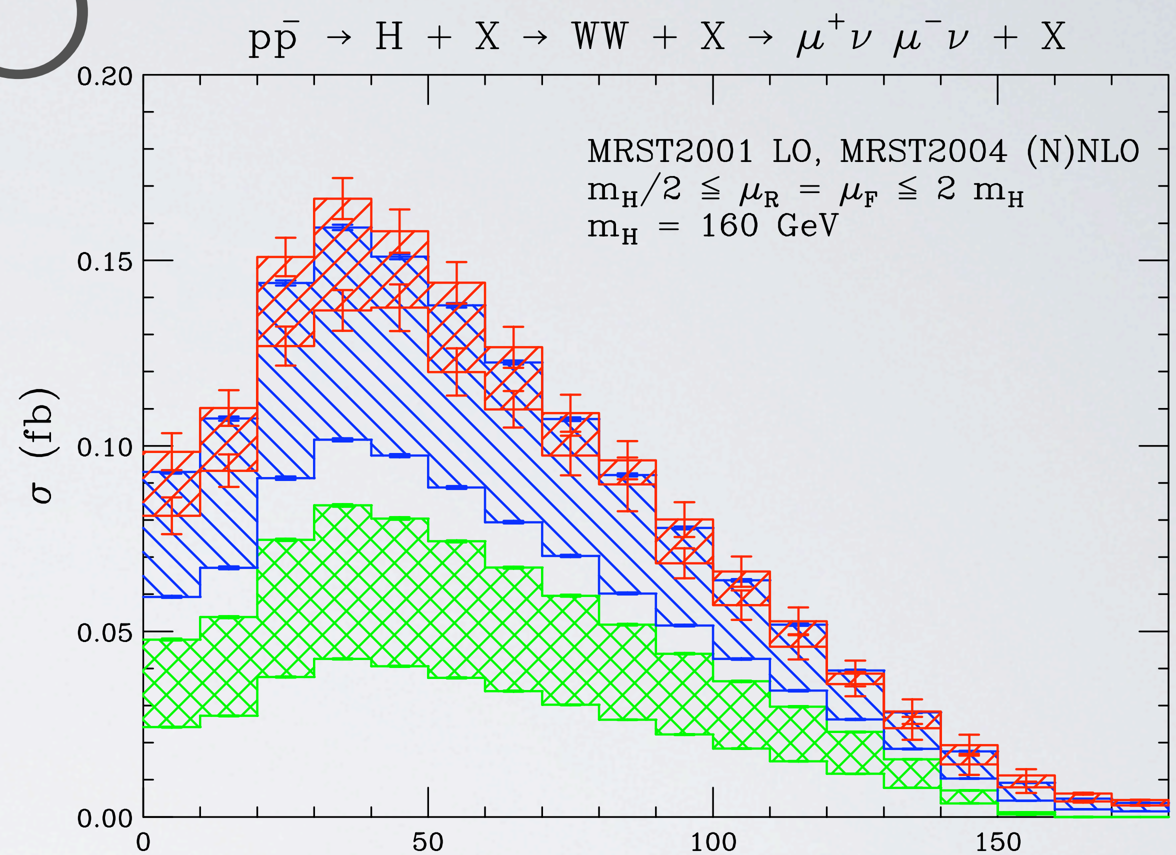


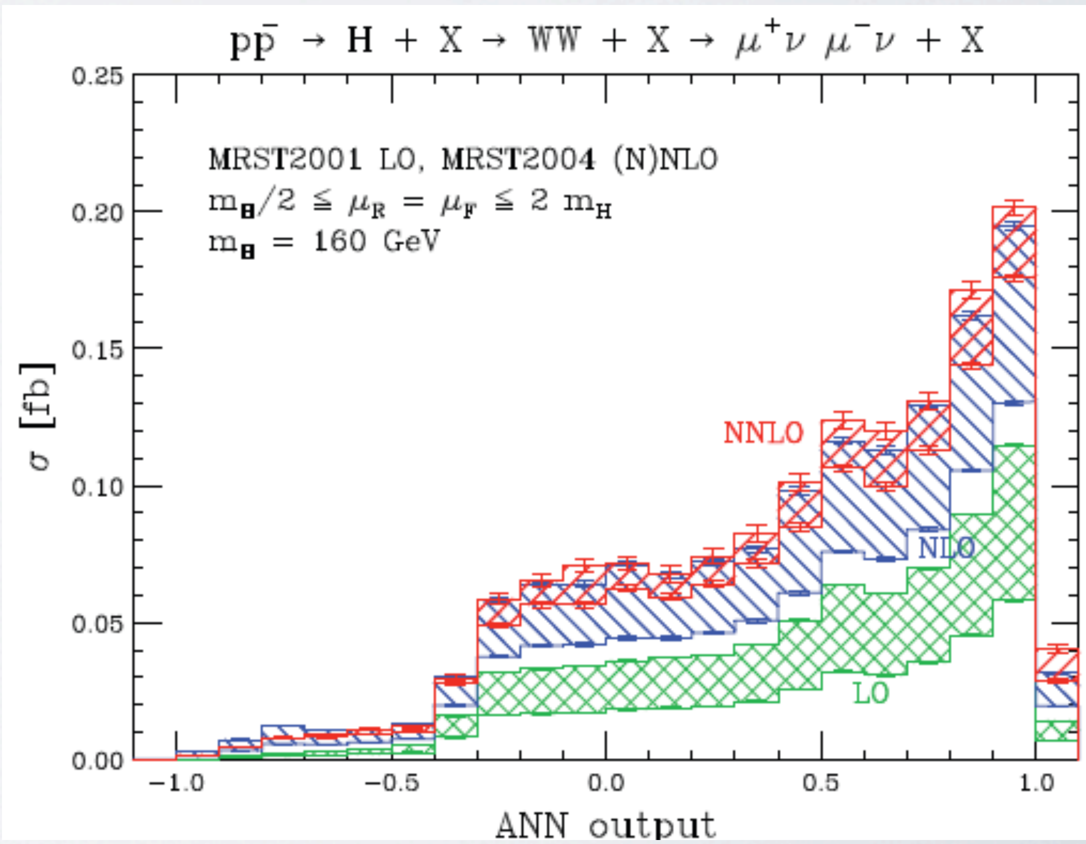
- TEVATRON exclusion with a detailed comparison of data with signal and background distributions

- important cuts on jets and lepton isolation

- Fully Exclusive Higgs Production (CA,Melnikov,Petriello; CA, Dissertori, Stoeckli)

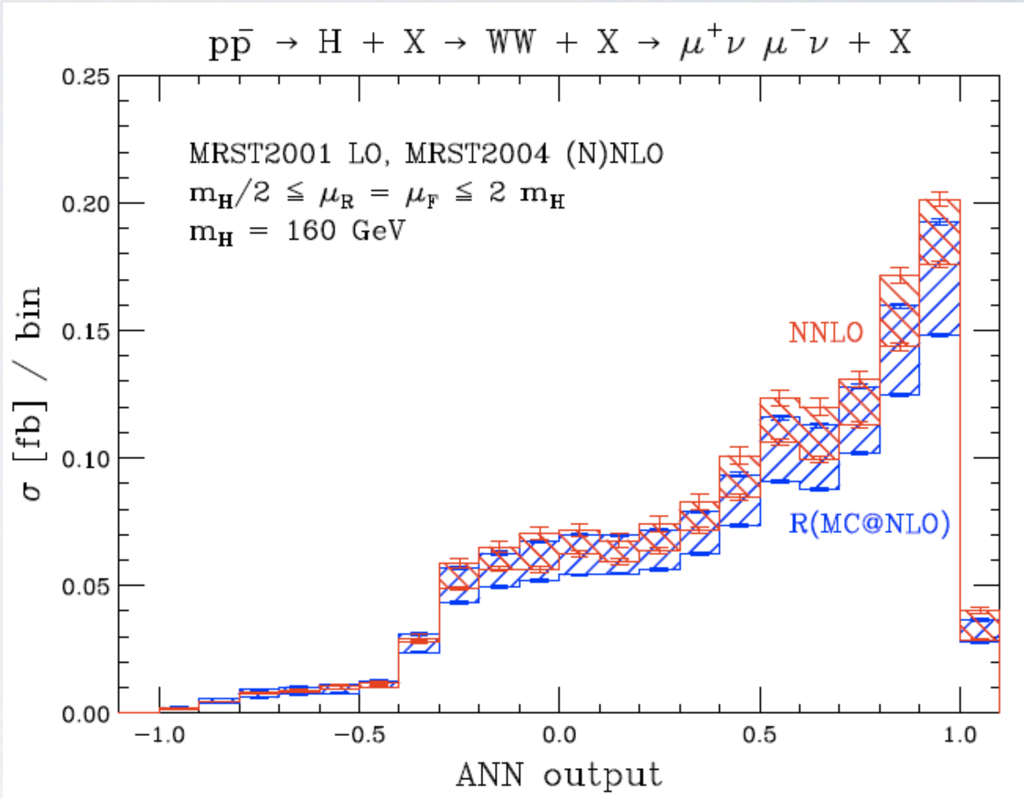
- HNNLO method (Catani,Grazzini; Grazzini)





GENERATORS DIFFER

- PYTHIA has a smaller jet-veto and isolation acceptance than HERWIG and MC@NLO
- HERWIG and MC@NLO closer to NNLO
- VALIDATION is indispensable!



(CA,Dissertori,Grazzini, Stoeckli,Webber)

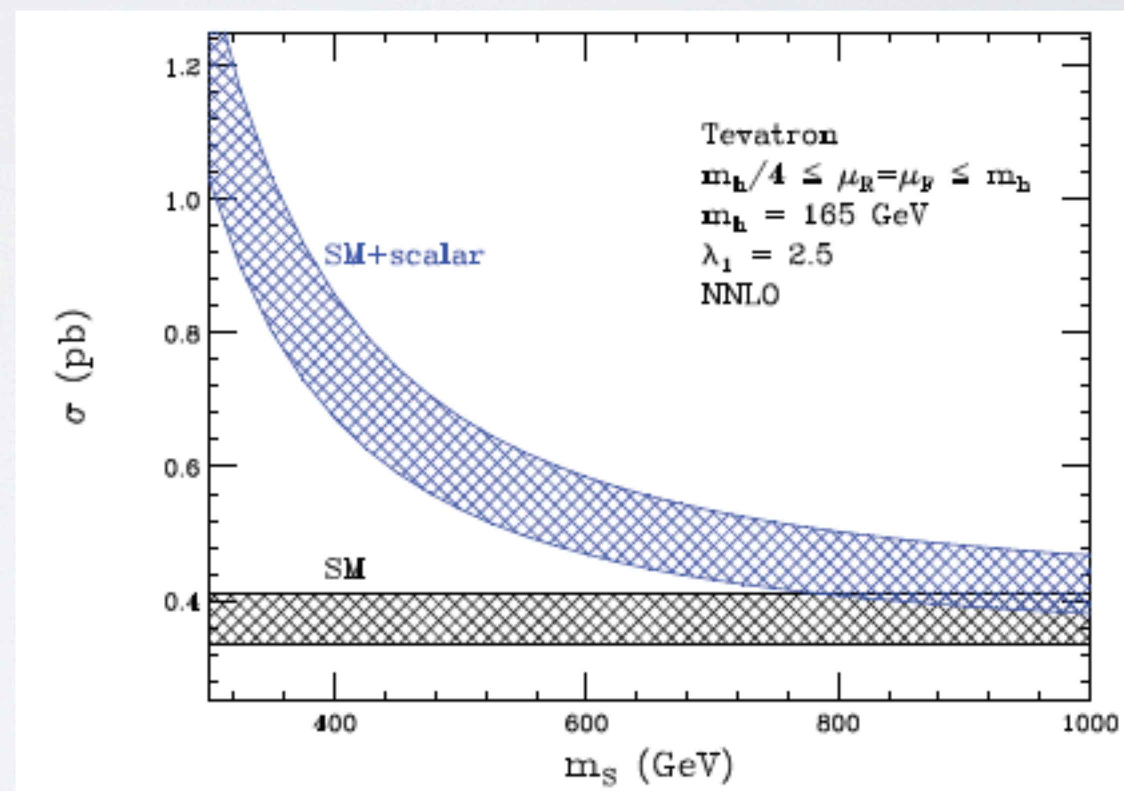
$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\ m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\ m_H$)	44.8%	38.8% (86.7%)	35.9% (92.5%)	27.0% (75.2%)
HERWIG	46.7%	40.8% (87.4%)	37.8% (92.7%)	28.6% (75.7%)
PYTHIA	46.6%	37.9% (81.3%)	32.2% (85.0%)	24.4% (75.8%)

BEYOND THE STANDARD GLUON FUSION

- Can we derive a mass exclusion limit for a BSM scalar Higgs boson from an experimental analysis based on SM theoretical predictions?
- very often yes, if QCD corrections and shapes of signal discriminants are model independent.
- CAN WE USE EXPERIMENTAL LIMITS OR A DISCOVERY AS PRECISION TESTS?
- Until recently no complete NNLO calculation for any extension of the SM (not even a fourth quark generation)

BSM HIGGS PRODUCTION AT NNLO

- Additional heavy quark families (CA, Boughezal, Furlan)
- Colour octet scalars (Boughezal, Petriello)



FUTURE NNLO PHENOMENOLOGY

- We need to develop methods that can be used for 2 to 2 scattering processes.
- Top-pair production, Di-boson production, and other routine processes will be simulated with high precision
- A big theoretical challenge, which requires additional efforts

RESUMMATION

- Progress in matching parton-showers and NLO calculations
  (MC@NLO:Webber,Frixione; White,Frixione,Laenen,Maltoni
  POWEHEG:Frixione,Nason,Oleari; Aliole,Nason,Oleari,Re;)

- Resummation in SCET
  thrust in ee, inclusive photons: Becher,Schwarz
  Drell-Yan and Higgs: Idilbi,Xi,Yuan,Ahrens,Becher,Neubert
  top-pair NLO+NNLL: Ahrens,Ferroglia,Neubert,Pecjak,Yang
  also Czakon, Mitov, Sterman

ITERATIVE PERTURBATION SERIES

- The perturbation series of gauge theories displays cross-order iterations.

- These are needed to cancel infrared and UV divergences, filtering the superposition principle from ultra short and very large distance effects.

- They are exploited to formulate parton shower algorithms, and resumming large logarithms.

- But, the remainder seems very different at each order in perturbation theory!

AN UNEXPECTED ITERATION IN N=4 SUPER YANG-MILLS THEORY

$$\mathcal{M}_4^{(2)}(\epsilon) = \frac{1}{2}\left(\mathcal{M}_4^{(1)}(\epsilon)\right)^2 + f^{(2)}(\epsilon)\mathcal{M}_4^{(1)}(2\epsilon) + C^{(2)} + \mathcal{O}(\epsilon)$$

CA, Bern, Dixon, Kosower

$$\mathcal{M}_n^{(2)}(\epsilon) = \frac{1}{2}\left(\mathcal{M}_n^{(1)}(\epsilon)\right)^2 + f^{(2)}(\epsilon)\mathcal{M}_n^{(1)}(2\epsilon) + C^{(2)} + \mathcal{O}(\epsilon)$$

$$\mathcal{M}_4^{(3)}(\epsilon) = -\frac{1}{3}\left(\mathcal{M}_4^{(1)}(\epsilon)\right)^3 + \mathcal{M}_4^{(2)}(\epsilon)\mathcal{M}_4^{(1)}(\epsilon) + f^{(1)}(\epsilon)\mathcal{M}_4^{(1)}(3\epsilon) + C^{(3)} + \mathcal{O}(\epsilon)$$

Bern, Dixon, Smirnov

$$\mathcal{M}_n = \exp\left[\sum_{l=1}^{\infty} a^l f^{(l)}(\epsilon)\mathcal{M}_n^{(1)}(l\epsilon) + C^{(l)} + \mathcal{O}(\epsilon)\right]$$

Can be computed in the strong limit with AdS/CFT Alday,Maldacena

$$\ln(1 + \sum_{l=1}^{\infty} a^l \mathcal{M}_n^{(l)}) = \ln(1 + \sum_{l=1}^{\infty} \mathrm{a}^l W_n^{(l)}) + \mathcal{O}(\epsilon)$$

<Wilson Loop> = Amplitude
Sokachev,Korchemsky

Can compute two-loop amplitudes with arbitrary number of legs, using the Wilson-loop duality

CA,Brandhuber,Heslop,Khoze,Spence,Travaglini

One-loop amplitudes from trees... and masters!!!

Trees in Gauge theory

Loop Master Integrals in scalar field theory

OUTLOOK

- Our abilities in simulating precisely collider processes have grown tremendously.
- New computational methods at NLO are extremely powerful. A classic work which will be part of future field theory books.
- Ready to take on the big challenge of finding new physics convincingly in hadron collider data.